Refinement of Rice Water Consumptive Use During the Growing Season — Sacramento Valley

Phase I — Field Study

By

Richard L. Snyder
Biometeorology Specialist

University of California, Davis

California Department of Water Resources

June 2018

Contractor: Office of the President, Regents of the University of California
University of California, Davis

Project Standard Agreement No. 4600008548A12TOUC101

State of California
Edmund G. Brown Jr., Governor

California Natural Resources Agency
John Laird, Secretary for Natural Resources

Department of Water Resources
Karla Nemeth, Director
Cindy Messer, Chief Deputy Director
Michelle Banonis, Assistant Chief Deputy Director

Office of the Chief Counsel
Spencer Kenner

Internal Audit Office
David Whitsell

Legislative Affairs Office
Kasey Schimke, Assistant Director

Public Affairs Office
Erin Mellon, Assistant Director

Tribal Policy Advisor
Anecita Agustinez

Office of Workforce Equality
Stephanie Varrelman

Deputy Directors

Business Operations
Kathie Kishaba

Delta Conveyance
Gary Lippner

Flood Management and Dam Safety
Eric Koch

Integrated Watershed Management
Kristopher Tjernell

Statewide Emergency Preparedness and Security
Christy Jones

Special Initiatives
Taryn Ravazzini

State Water Project
Joel Ledesma

Division of Statewide Integrated Water Management
Kamyar Guivetchi, Manager

Statewide Infrastructure Investigations Branch
Ajay Goyal, Chief

Prepared by
Tom Filler, DWR Project Manager
Richard L. Snyder, Lead Scientist, University of California, Davis

Contents

Tables

Figures

Abbreviations and Acronyms

Cal-SIMETAW	California Simulation of Evapotranspiration of Applied Water
CETc	cumulative crop evapotranspiration
CIMIS	California Irrigation Management Information System
cm	centimeter
DWR	California Department of Water Resources
ETaw	evapotranspiration of applied water
ETc	crop evapotranspiration
ETo	reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
G	ground heat flux
H	sensible heat flux density
Kc	crop coefficient
km	kilometer
LE	latent heat flux density
mm	millimeter
OCETc	cumulative observed crop evapotranspiration
OETc	observed crop evapotranspiration
OETci	observed daily crop evapotranspiration
PCETc	cumulative predicted crop evapotranspiration
Pe	effective rainfall
PETc	predicted crop evapotranspiration
PETci	predicted daily crop evapotranspiration
ra	aerodynamic resistance
rac	aerodynamic resistance of the crop
rcc	canopy resistance of the crop
REB	residual of the energy balance
RMSE	root mean square error
Rn	net radiation
Rs	solar radiation
SIMETAW	Simulation of Evapotranspiration of Applied Water
UC	University of California
UC Davis	University of California, Davis
W	watt

Acknowledgments

Richard Snyder, Ali Montazar, Honza Rejmanek, and Gwen Tindula (University of California, Davis); Cass Mutters, James Hill, and Bruce Linquist (University of California Cooperative Extension Farm Advisors); and Cayle Little, Morteza Orang, Tom Hawkins, Tito Cervantes, Mark Rivera, Todd Hillaire, Al Vargas, Julie Haas, Chris McCready, Scott Woodland, Tom Filler and Ajay Goyal (California Department of Water Resources).

Executive Summary

The purpose of this study is to evaluate crop water use for the most commonly grown paddy rice variety grown in the Sacramento Valley, M206, based on field data collected from 2007 through 2009, and from 2011 through 2013. M206 was identified by the University of California (UC) Cooperative Extension Farm Advisors as the most commonly grown rice variety in the study area. Phase I of this study was conducted by the University of California, Davis (UC Davis), under contract with DWR. A brief description of both Phase I and Phase II have been included here to provide orientation as the progression of the work and linkages between each phase regarding the study results.

Phase I of the *Refinement of Rice Water Consumptive Use During the Growing Season* consists of a field study. It was prepared by Richard Snyder of UC Davis. It is based on the evapotranspiration (ET) data collected from nine paddy rice fields in the Sacramento Valley from 2011 to 2013. This study used energy balance techniques to develop a typical Kc curve.

A crop coefficient is the ratio of crop evapotranspiration (ETc) to reference evapotranspiration (ETo). ETo is an estimate of evapotranspiration rate of a 4- to 6-inch tall, well irrigated, cool-season grass.

$$\mathrm{Kc} = \frac{\mathrm{ETc}}{\mathrm{ETo}}$$

Phase II of the *Refinement of Rice Water Consumptive Use Estimates During the Growing Season* consists of a Cal-SIMETAW model study. It was prepared by the California Department of Water Resources (DWR) and uses the newly developed Kc curve to estimate seasonal cumulative evapotranspiration of rice (CETc) for each of the California Water Plan's 19 detailed analysis units/counties within the Sacramento Valley from 1987 to 2016, based on 2014 land use data.

The data gathered during Phase I of the study will be used to update the crop coefficient (Kc) values published in DWR Bulletin 113-4, *Crop Water Use in California* (California Department of Water Resources 1986), for rice grown in the Sacramento Valley. The Kc values are widely used by DWR and others to help estimate crop water use through evapotranspiration. Research indicates that the Kc values used in Bulletin 113-4 were taken directly from DWR Bulletin 113-3 (California Department of Water Resources 1975). When Bulletin 113-3 was published in 1975, summarizing the growing season evapotranspiration and evapotranspiration of applied water for principal crops grown in major agricultural regions of the state, the Standardized Reference Evapotranspiration (ETref) equation for short canopies (ETo), did not exist. At that time, ETo was mainly estimated using pan evaporation.

While pan evaporation can provide good estimates of ETo when averaged over several days, it is not as accurate on as daily basis. Based on considerable research in recent decades, there is good confidence that the hourly ETo equations are accurate, and the 24-hour sums provide good daily ETo estimates regardless of the climate. In addition, the height of M206 rice variety is approximately two-thirds of the height of varieties planted in the late 1960s. The change in crop height and use of the ETo equation, rather than pan evaporation, might explain a higher Kc in the past.

The product of reference evapotranspiration (ETo) and Kc values continues to be one of the most commonly used methods for estimating crop evapotranspiration (ETc) for irrigation planning and management decisions. ETo approximates the evapotranspiration of a well-irrigated pasture and is intended to account for variations in weather. The Kc factor accounts for biological, agronomic, and eco-physiological differences between the crop under study and the ETo. The Kc factor is determined as an ETc/ETo ratio using simultaneous calculation of ETo and field measurements of ETc. In this study, ETo was estimated from nearby California Irrigation Management Information System (CIMIS) station weather data or Spatial CIMIS data (Hart et al. 2009). The ETc was measured using the residual of the energy balance (REB) method, which is based on micro-meteorological measurements.

This study revisits Sacramento Valley rice Kc values using state-of-the-art equipment and current scientific understanding of evapotranspiration. Specifically, this study uses the Food and Agriculture Organization of the United Nations (FAO) procedure first recommended by Doorenbos and Pruitt (1977) and later by Allen et al. (1998). This methodology has also been incorporated into the DWR Simulation of Evapotranspiration of Applied Water (SIMETAW) and the California Simulation of Evapotranspiration of Applied Water (Cal-SIMETAW) programs.

SIMETAW and Cal-SIMETAW are models developed by DWR and UC Davis to perform daily soil water balance for estimating ETc and evapotranspiration of applied water (ETaw) for use in California Water Plan Update 2018.

For this study, field experiments to measure rice ETc were conducted in three paddy rice fields per year, for a total of nine fields during the 2011–2013 growing seasons in the Sacramento Valley (Figure ES-1). In addition, evaporation from bare soil in a rice field without irrigation was monitored at the Rice Experiment Station near Biggs to evaluate soil moisture loss from fallowed fields. A complete description of the research locations, instrumentation, and methods used is given in Appendix A.

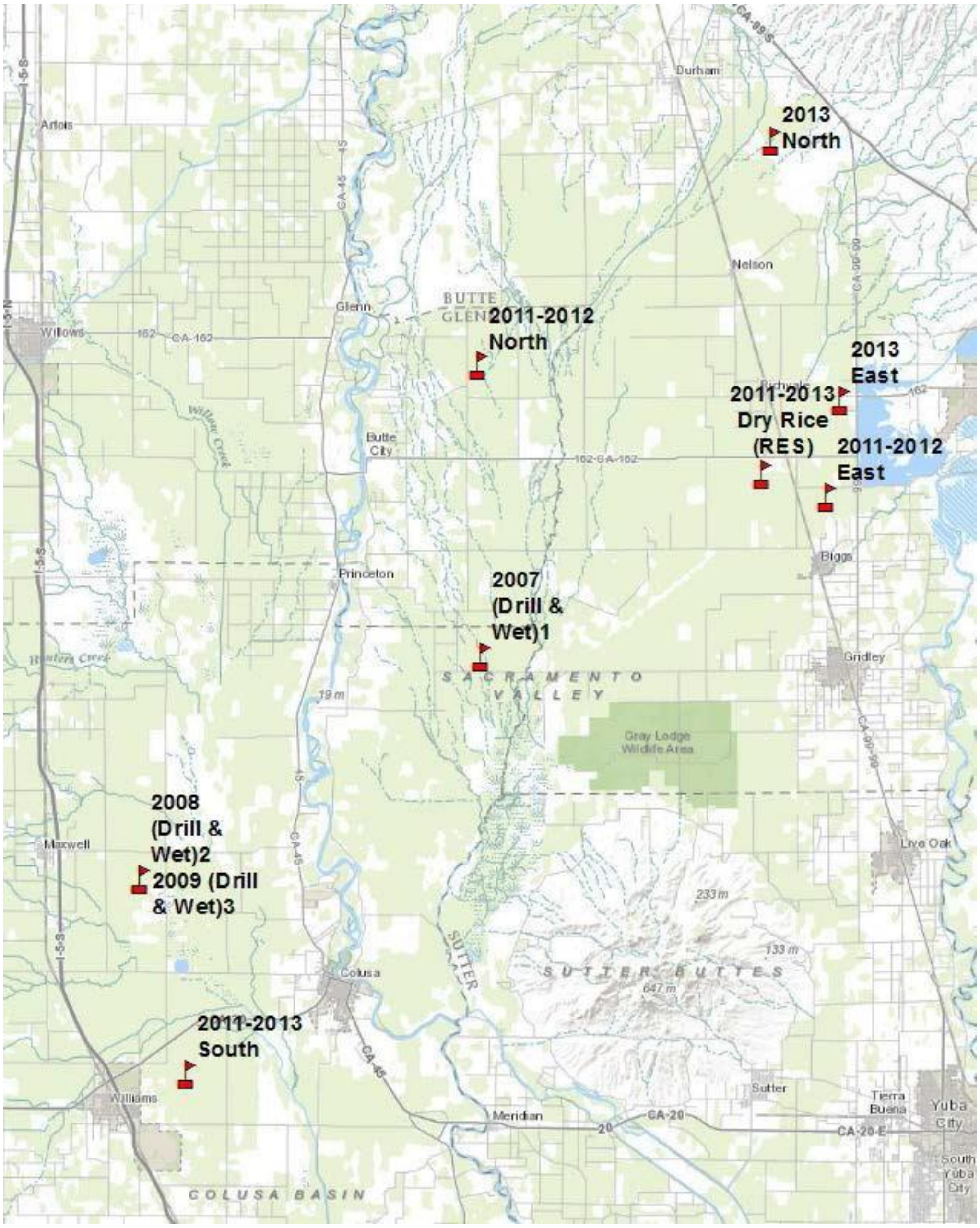
Data collected in an earlier 2007–2009 study of the evapotranspiration of drill-seeded and wet-seeded rice were used to validate the 2011–2013 data.

Data and results collected and published in the *Effect of Low Water Temperature on Rice Yield in California* (Mutters, et al. 2005), which DWR and others had collaborated on regarding the effects of colder water temperatures on rice, are not considered or referenced as part of this report.

No data related to rice water use, or rice growing cultural practices, was collected or analyzed pre- or post-growing season. This report focuses on the development of a rice Kc for water use by the evapotranspiration of rice during the time period of the average crop first flood-up in mid-spring to average crop senescence and harvest in late summer and early fall. Further studies are needed to evaluate rice water use associated with rice stubble decomposition and other cultural practices associated with growing rice in the Sacramento Valley.

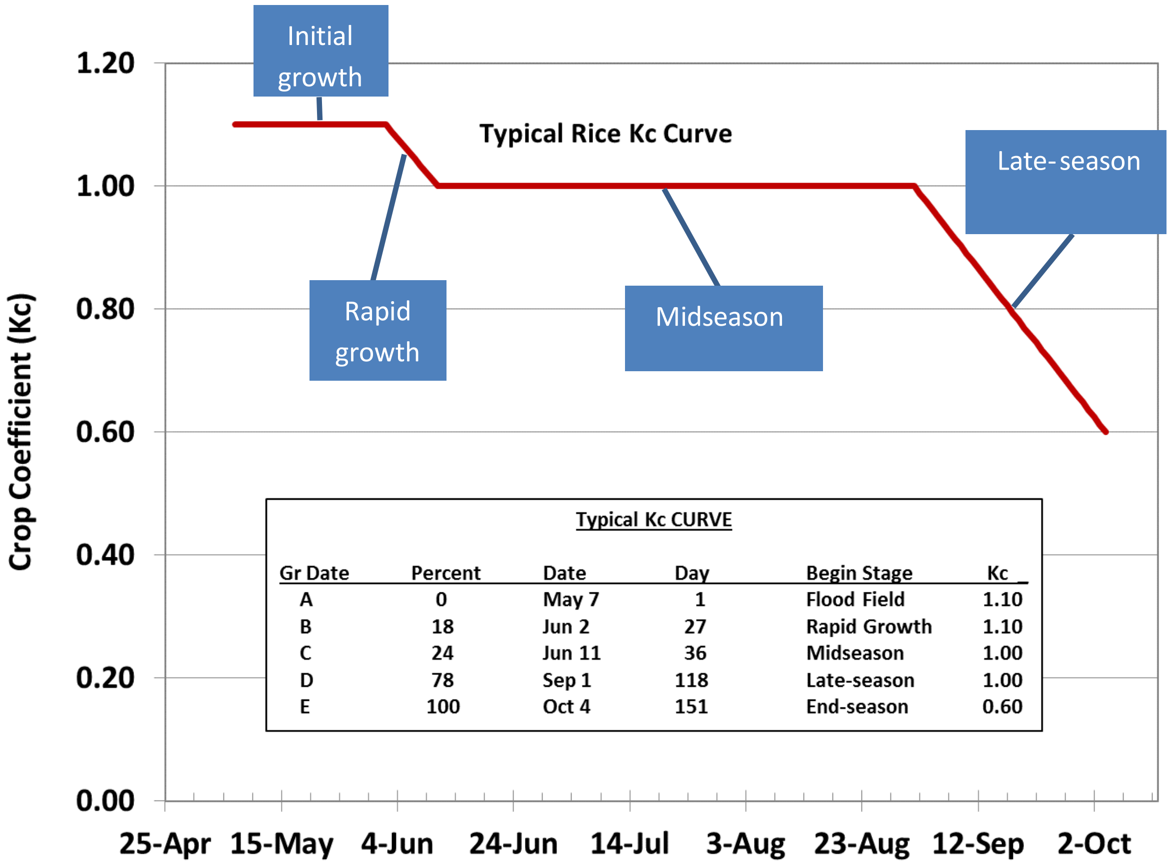
Based on the field experiments in this report, a “typical” crop coefficient curve for M206 rice variety was developed for the Sacramento Valley. The seasonal cumulative ETc (CETc) was 34.0 inches based on daily mean ETo from the Colusa CIMIS station. Measurements over unirrigated bare soil demonstrated a seasonal bare-soil evaporation of 4.1 inches.

Figure ES-1. **Locations of Experimental Fields**



The typical Kc curve for M206 rice in the Sacramento Valley developed in this study is shown in Figure ES-2. The curve was developed from the 2011–2013 data, which was validated using the 2007–2009 data results, and then "normalized" using typical growth dates provided by the UC Cooperative Extension Farm Advisors.

Figure ES-2. Typical Kc Curve Derived from Data Applied to the Recommended Growth Dates for the M206 Variety in the Sacramento Valley (2011–2013)



Typical Kc CURVE

Gr Date	Percent	Date	Day	Begin Stage	Kc
A	0	May 7	1	Flood Field	1.10
B	18	Jun 2	27	Rapid Growth	1.10
C	24	Jun 11	36	Midseason	1.00
D	78	Sep 1	118	Late-season	1.00
E	100	Oct 4	151	End-season	0.60

The Kc curve shape is defined by four distinct periods of the rice growth cycle:

- A–B: Initial growth.
- B–C: Rapid growth.
- C–D: Midseason.
- D–E: Late season.

The Kc value is assumed constant during the initial growth period (A–B), which is the period from first flooding until the crop canopy shades approximately 10 percent of the surface. The typical Kc curve decreases linearly during rapid growth period (B–C). During midseason (C–D), from the time that the canopy shades approximately 75 percent of the surface until the onset of senescence, the Kc value is constant. In late season (D–E), the typical Kc values decrease linearly from D to E. For M206 rice variety grown in the Sacramento Valley, the season, on average, is determined to be approximately 151 days. The typical growth periods, recommended by UC Cooperative Extension Farm Advisors and specialists, are: (A) May 7, for field flood-up, (B) June 2, for rapid growth, (C) June 11, for full albedo development of canopy, (D) September 1, for the beginning of crop senescence, and (E) October 4, for crop maturity. Harvest occurs after the crop is mature. The dates are based on many years of field observations, water diversion data collected by DWR, and data provided by major seed and drying purveyors. Actual growth dates may vary considerably from year to year, usually depending on factors related to weather that influence when tillage can begin and planting can occur. Appendix D has additional data on water diversion, seed distribution, and rice crop drying.

Using the typical Kc curve developed in this study (Figure ES-2) and the historic mean daily ETo from the Colusa CIMIS station, the average seasonal ETc during the period 1986 through 2010, was estimated to be 34.0 inches (2.80 feet). Using the typical Kc curve developed in this study, DWR's Cal-SIMETAW model was used to determine a weighted-mean estimate of CETc for rice for the Sacramento Valley from 1987 through 2016. The study value of 34.0 inches (2.80 feet) compares closely with the weighted average seasonal ETc for rice in the Sacramento Valley of 34.4 inches (2.9 feet), computed using Cal-SIMETAW for 1987 through 2016. In the future, Cal-SIMETAW could be used to update the average ETc as needed.

1. Introduction

This report summarizes findings of a crop water-use study for paddy rice grown in the Sacramento Valley based on field data collected from 2007 through 2009, and from 2011 through 2013. The data gathered during this study will be used to update the crop coefficient (Kc) values for rice grown in the Sacramento Valley as published in the California Department of Water Resources (DWR) Bulletin 113, *Crop Water Use in California* (California Department of Water Resources 1986). The Kc values are then used to estimate crop evapotranspiration (ETc) from a computed daily reference evapotranspiration (ETo). The study was conducted by the University of California, Davis (UC Davis) under contract with DWR.

1.1. Background

From 2007 through 2009, a preliminary field study of rice crop evapotranspiration was conducted by UC Davis under contract with DWR. Field data from 2007 through 2009 showed Kc values that were lower than those commonly used to estimate rice ETc during the midseason, and were higher than expected during early growth (before canopy closure).

Subsequent field studies were performed from 2011 through 2013 using state-of-the-art instrumentation and advanced data collection techniques. A Kc curve derived from the 2011–2013 data confirmed findings of the previous studies performed from 2007 through 2009. The derived Kc curve was vetted with subject matter experts, including Rick Snyder (UC Davis), Cass Mutters, and Bruce Lindquist (University of California [UC] Cooperative Extension Farm Advisors), and Cayle Little, Morteza Orang, Tom Hawkins, Tito Cervantes, Mark Rivera, Al Vargas, Todd Hillaire, and Tom Filler (DWR).

No data related to rice water use, or rice growing cultural practices, was collected or analyzed pre- or post-growing season. This report focuses on the development of a rice Kc during the time period of the average crop first flood-up in mid-spring to average crop senescence and harvest in late summer and early fall. Further studies are needed to evaluate rice water use associated with rice stubble decomposition and other cultural practices associated with rice growing in the Sacramento Valley.

1.2. Purpose

The purpose of this study was to evaluate crop water use for the most commonly grown paddy rice variety grown, M206, in the Sacramento Valley. This study used state-of-the-art instrumentation and current scientific understanding of evapotranspiration processes of irrigated paddy rice fields.

The information developed by this study, when combined with data on the acreage of specific rice crop production and ETo data from the California Irrigation Management Information System (CIMIS), can help to provide knowledge of the location, nature, and amount of water used for rice production throughout the Sacramento Valley. Such information can support many different efforts DWR is engaged in, including those conducted to determine (1) developing water supply shortages or the availability of water supply for local use and/or export to other areas of need, (2) the ability of users to pay for additional water supplies, (3) optimum reservoir operations, (4) the rate of groundwater extractions, (5) the potentials for water savings through increased water use efficiency, (6) the location, nature, and amount of water quality deterioration caused by agricultural chemicals, (7) current and potential soil water drainage problems, and (8) other water-resource-related matters.

2. Methodology

This study updates the Kc curve for rice in the Sacramento Valley using the procedure recommended by the Food and Agriculture Organization of the United Nations (FAO). The procedure is described in FAO Irrigation and Drainage Paper No. 56, *Crop Evapotranspiration (guidelines for computing crop water requirements)* (Allen et. al., 1998) and FAO Irrigation and Drainage Paper No. 24, *Guidelines for predicting crop water requirements* (Doorenbos and Pruitt 1975). This methodology has also been incorporated into the DWR Simulation of Evapotranspiration of Applied Water (SIMETAW), and the California Simulation of Evapotranspiration of Applied Water (Cal-SIMETAW) programs.

2.1. Overview of Crop Evapotranspiration Processes and Estimation

Evapotranspiration is a measure of combined water losses from two processes: evaporation and transpiration. In evaporation, water is lost from a surface to the atmosphere through a phase change from liquid to vapor. For example, water is evaporated from surfaces including lakes, hard surfaces (e.g., pavement), soil, and vegetation. In transpiration, water contained inside plant tissues is vaporized and the water vapor passes through plant pores, or “stomata,” to the ambient air.

When a rice crop is young, evaporation dominates the evapotranspiration losses, because the crop canopy is small, leaving significant water surface area exposed. As the rice crop matures, the crop canopy shades the water surface, and transpiration begins to dominate the evapotranspiration losses.

Evapotranspiration is affected by many factors, including weather, crop type, farming methods, soil type, and climate. Primary weather parameters influencing evapotranspiration include solar radiation, air temperature, humidity, and wind speed. Evapotranspiration can change markedly with small changes in weather, such as a shift in cloud cover. Those weather changes are detectable through continuous sampling. On a regional scale, evapotranspiration reveals a strong correlation to crop development periods (e.g., early-, mid-, and late-season) for a specific crop type in a particular region. As a result, it is possible to generalize evapotranspiration, using a typical Kc curve, and it can be used to estimate total seasonal evapotranspiration.

Evapotranspiration is difficult and expensive to measure directly. As a result, it is typically estimated using equations based on nearby weather data. ETc for a particular crop and location is commonly computed as the product of a Kc and ETo:

$$ETc = Kc \times ETo \qquad (1)$$

The ETo is a climatic parameter representing the evaporative capacity of the atmosphere at a particular location and time of year, and can be computed from weather data. Technically, ETo represents the evapotranspiration of a virtual crop having a fixed value for canopy resistance and an inverse function of the wind speed for the aerodynamic resistance. The commonly used standardized reference evapotranspiration equations (i.e., modified Penman-Monteith equations), give ETo rates that are limited only by energy and not by water or salinity stress. But, in practice, ETo rates are similar to the evapotranspiration of a 12-centimeter (cm) tall, cool-season grass, assuming no water or salinity stress.

Kc values are commonly determined through field experiments that carefully measure ETc over time for a particular crop, management method, and location. The experimental ETc values are coupled with ETo values calculated from climatic data at the same location to determine the Kc as:

$$\mathrm{Kc} = \frac{\mathrm{ETc}}{\mathrm{ETo}} \tag{2}$$

It is assumed that the Kc will be the same in subsequent years under similar crop and management conditions. The Kc values vary with a crop's growth rate, which depends on local climate. The remainder of this section describes the specific methodology used in this study to develop Kc curves for M206 rice grown in the Sacramento Valley.

2.2. Field Methods to Determine Crop Evapotranspiration

Micrometeorological weather stations were set up in each of the rice paddies to measure all necessary parameters to estimate the evapotranspiration for rice. Each station incorporated the following equipment:

- CR3000 Campbell Scientific data logger.
- RM Young 81000RE sonic anemometer.
- NR Lite II net radiometer by Kipp & Zonen.
- Soil and water temperature sensors.
- Soil heat flux sensors.
- Water level sensors.
- 76 µm diameter fine-wire, chromel-constantan thermocouple.
- Assorted weather sensors.

Station data retrieval was via cellular modems. The sonic anemometer was used to measure sensible heat flux density (H) using the eddy covariance method following Lee et al. (2004). In addition, the fine-wire thermocouple was used to measure H using the surface renewal method described in Shapland et al. (2013). Additional information on the surface renewal method is reported in Paw U et al. (1995), Snyder et al. (1996), Spano et al. (1997), Chen et al. (1997) Spano et al. (2000), and Paw U et al. (2005). All data collected prior to 2013 were reanalyzed using the Shapland et al. (2013) modification of the van Atta function. Both H values were used to calculate the latent heat flux density (LE) using the REB approach equation (LE = Rn - G - H) where Rn is net radiation and G is ground heat flux. Note that there was no infrared gas analyzer used in these experiments. Direct LE measurements were not used in these experiments because they are known to underestimate the real LE values for most irrigated crops (Stoy et al. 2013).

In using the REB method, it is assumed that the Rn, G, and H values are accurately measured. Based on 25 years of experiments and comparisons with lysimeter and other methods, the REB method is widely accepted by the scientific community. Because the eddy covariance and surface renewal methods provide a separate means of calculating the sensible heat flux, having similar results provides additional confidence in the data. The G at the surface was calculated using heat flux plate measurements corrected for soil heat storage in the surface soil layers. The LE was calculated with the REB equation using rotated eddy covariance H values whenever data were available. Otherwise, surface renewal H-values were used. A more detailed description of the micrometeorological station set up, instrumentation, and analysis to obtain ETc is given in Appendix A.

2.3. Computational Methods to Determine Reference Evapotranspiration

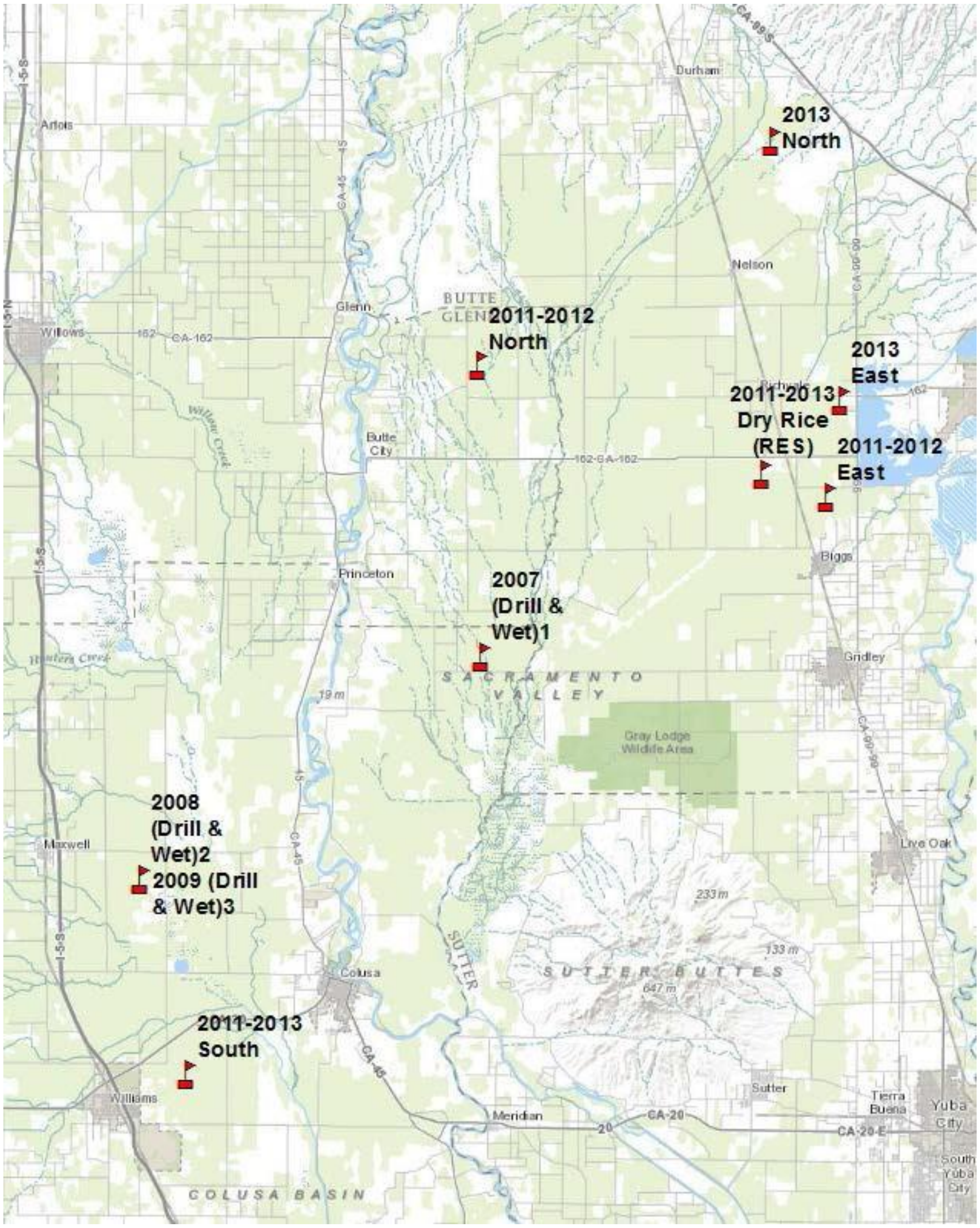
While there are several CIMIS weather stations for estimating ETo in the Sacramento Valley, some of them are widely spaced and not close to the experimental fields. Consequently, the ETo in this study was retrieved from Spatial CIMIS at the latitude and longitude of the experimental fields. Spatial CIMIS is a statewide geospatial raster dataset developed by DWR and UC Davis to estimate ETo at locations between CIMIS stations. The ETo calculations were made using GIS and temperature, humidity, and wind speed data from CIMIS weather stations, and solar-radiation data generated from the visible band of the National Oceanic and Atmospheric Administration's Geostationary Operational Environmental Satellite using the Heliosat-II model. Solar radiation, temperature, relative humidity, and wind speed are determined for a 2-kilometer (km) grid over the state. The generated values were used to estimate daily ETo on the 2-km grid using the daily ETo equation for short canopies from Allen et al. (2006).

2.4. Study Site Selection

Study sites were selected based on the presence of representative characteristics to measure ETc. For example, each site required adequate fetch to ensure that the instrumentation was accurately measuring sensible heat flux, heat storage in the water, and net radiation from a part of the rice paddy that was representative of the evapotranspiration from the field. Multiple sites within the Northern Sacramento Valley were desired in order to clearly account for any local effects on ETc estimates. Multiple stations in varying locations were sought to manage variability of practices and microclimates between individual growers. Sites were selected based on several criteria including appropriate location in the desired growing region, appropriate field size ensuring adequate wind fetch, uniform variety, standard grower practices, and cooperative land owners. Using four geographically independent sites allowed us to generalize the results for the majority of the rice grown in Northern California.

Figure 1 shows the location of the experimental fields. The site names indicate each site's relative location (e.g., north, east, or south) and the year(s) of monitoring at that location.

Figure 1. **Locations of Experimental Fields**



2.5. Development of Crop Coefficient Curves Identifying the Growth Dates

Key growth dates that serve as inflection points in the Kc curve were determined by plotting the ratio of net radiation (Rn) and solar radiation (Rs). The ratio of Rn/Rs was used to identify the inflection points of the Kc curve because it eliminates minor fluctuations in Kc values related to the other factors. It is well-known that Rn measured over grass is typically about 67 percent of Rs, but in these studies, the ratio Rn/Rs for rice was observed to change during the season. Because rice LE mainly depends on Rn, it is also likely that both Rn and LE will change in a similar manner relative to Rs during the season, as discussed further in Section 3.1.

A plot of the Rn/Rs ratio during an entire rice season (Figure 2) clearly reveals the start and end dates of each of the following growth periods:

- A–B: Initial growth.
- B–C: Rapid growth.
- C–D: Midseason.
- D–E: Late season.

Rs data was available as a continuous time series at daily increments from the Spatial CIMIS data published by DWR. Rn was reported at the 12 fields (including the bare field) at half-hour increments. The Rn was computed as the daily sum of the half-hourly Rn energy received. The ratio of daily average Rn/Rs was used to remove the variation caused by weather variables to identify the end points of the growth periods. After defining the end points, the best fit Kc curve was found by iteration within each growth period. The information was verified by UC Cooperative Extension Farm Advisors and specialists who recommended a season length of 145 days, and identified typical average growth dates (A, B, C, D, and E). Overall, the 2013 Rn data set had the fewest missing data points of all of the years collected. The planting dates and end dates were similar at all three rice fields in 2013, so that year was selected to identify typical growth dates.

It is assumed that the relative length of each growth period is approximately constant from year to year. Thus, the percentage of season to the end of each growth period was computed from the 2013 data and applied to the other years to determine their respective growth dates.

2.6. Deriving Crop Coefficients

2011–2013 Procedures

Field monitoring data collected from 2011 through 2013 was used to compute a time series of observed crop evapotranspiration (OETc). A Kc curve was developed iteratively, using equations (3) and (4) to achieve the best match of predicted crop evapotranspiration (PETc) and OETc values:

$$\text{PETc} = \text{ETo} \times \text{Kc} \qquad (3)$$

where ETo was taken from Spatial CIMIS (Hart et al. 2009) for the coordinates of each experimental field. The 2013 best fit Kc curve was determined for each of the experimental fields by varying initial growth Kc (Kc1), midseason Kc (Kc2), and the Kc on date E (Kc3) until the root mean square error (RMSE) of the daily predicted, versus the daily observed, crop evapotranspiration was minimized. The RMSE is a measure of how well two sets of data match a 1:1 line. An RMSE close to zero indicates that the prediction matches the observations well. The RMSE is calculated as:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\text{PET}_{ci} - \text{OET}_{ci})^2}{n}} \qquad (4)$$

where PET_{ci} is the predicted daily crop evapotranspiration computed using equation (1) and OET_{ci} is the observed daily crop evapotranspiration on the i-th day of n pairs of predicted and observed data. The RMSE was calculated separately every year for each of the three experimental fields from 2011 through 2013. An overall RMSE for all of the fields and years was also computed. Minimizing the overall RMSE was used to identify the optimal Kc values.

The seasonal cumulative predicted crop evapotranspiration (PCETc) and seasonal cumulative observed crop evapotranspiration (OCETc) were determined for each of the experimental fields. The RMSE of the PCETc versus OCETc was determined using the nine experimental field data sets for 2011 through 2013. On days when there were missing OETci data, the PETci value was substituted on that date. In the 2011–2013 dataset, there were only 5 days of missing data from the 2012 east experimental field.

2007–2009 Procedures

To further validate the applicability of the Kc curve developed using 2011–2013 data to other years, the daily Kc values were used to compute predicted PETc for 2007 through 2009 from a record of observed ETo. The daily 2007–2009 PETc and OETc data were then compared using the RMSE for all experimental field/year combinations. As with the 2011–2013 data, the 2007–2009 PCETc and OCETc data were computed and compared using the RMSE.

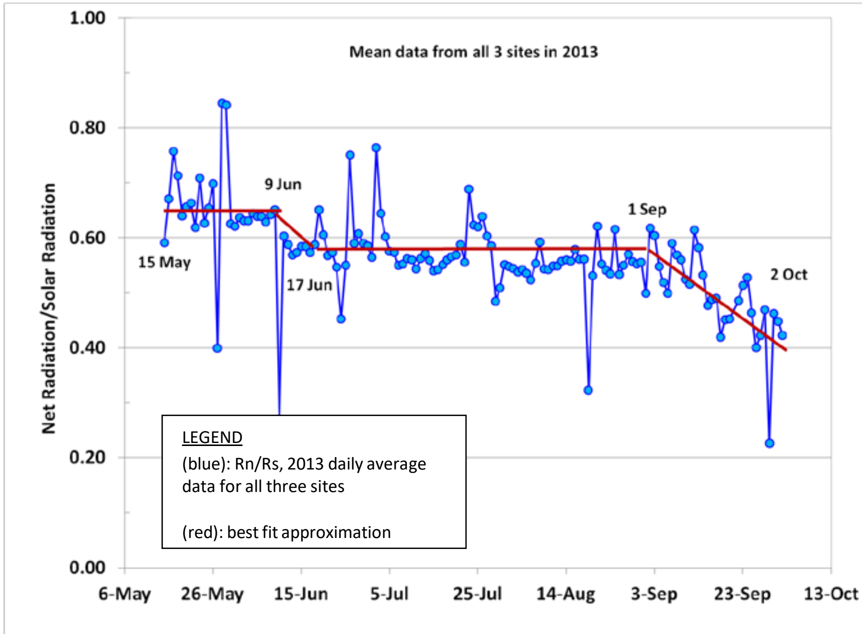
3. Results and Discussion

3.1. Growth Dates

Growth dates to define the ends of growth stages were identified from a plot of Rn/Rs using daily Rn data from the three fields in 2013 (Figure 2). The dates identify the growth dates at the Kc inflection points in the curve. From Figure 2, the growth dates for 2013 were determined to be: (A) May 15, for field flood-up, (B) June 9, for the onset of rapid growth, (C) June 17, for full albedo development of canopy, (D) September 1, for the beginning of crop senescence, and (E) October 2, for crop harvest. The corresponding percentages of season to date are: A–B (18 percent), A–C (24 percent), and A–D (78 percent). They are assumed to apply for M206 variety in any season. The dates were used to determine an estimate of the best fit Kc curve for 2013. The planting in 2013 was a couple of weeks later than in a typical year, so the growth dates were adjusted to provide a set of typical growth dates for M206 variety in the Sacramento Valley.

For M206 rice grown in the Sacramento Valley, the season, on average, is determined to be about 151 days. The typical growth dates, as recommended by UC Cooperative Extension Farm Advisors and specialists, are: (A) May 7, for field flood-up, (B) June 2, for the onset of rapid growth, (C) June 11, for full albedo development of canopy, (D) September 1, for the beginning of crop senescence, and (E) October 4, for crop harvest. The dates are based on many years of field observations, water diversion data collected by DWR, and data provided by major seed and drying purveyors. Actual growth dates may vary considerably from year to year, usually depending on factors related to weather that influence when tillage can begin and planting can occur. Appendix D has additional data on water diversion, seed distribution, and rice crop drying.

Figure 2. Rn/Rs Ratio (2013) with Best Fit Approximation



Note:
Rn = net radiation, Rs = solar radiation

3.2. Crop Coefficient Curves

Figure 3 depicts the 2013 best fit Kc curve for rice using the growth dates estimated in Section 3.1. The Kc value is relatively constant during the initial growth period (A–B), which is the period from first flooding until the crop canopy shades approximately 10 percent of the surface. The Kc decreases approximately linearly during rapid growth (B–C) and, during midseason (C–D), from the time that the canopy shades approximately 75 percent of the surface until the onset of senescence, the Kc is constant again. In late season (D–E), the Kc decreases approximately linearly. This section discusses how the Kc values in Figure 3 were determined.

The Kc values in Figure 3 were found by using the observed beginning date (A) and ending date (E) for each of the three fields from 2011 through 2013, and the percentages of the season (18 percent, 24 percent, and 78 percent) from Section 3.1 to determine the growth dates B, C, and D, and identify the growth periods. The daily Kc values for initial growth (Kc1), midseason (Kc2), and at the end of the season (Kc3) were iterated and a daily PETc was calculated for each field in each season using Equation 3. The iteration was done until the RMSE of the daily PETc versus OETc over the nine studied rice paddies, was minimized. The best fit Kc values were Kc1 = 1.1 during initial growth, Kc2 = 1.0 during midseason, and Kc3 = 0.6 on date E. The derived seasonal Kc curves are plotted using the 2013 mean growth dates from Section 3.1 in Figure 3.

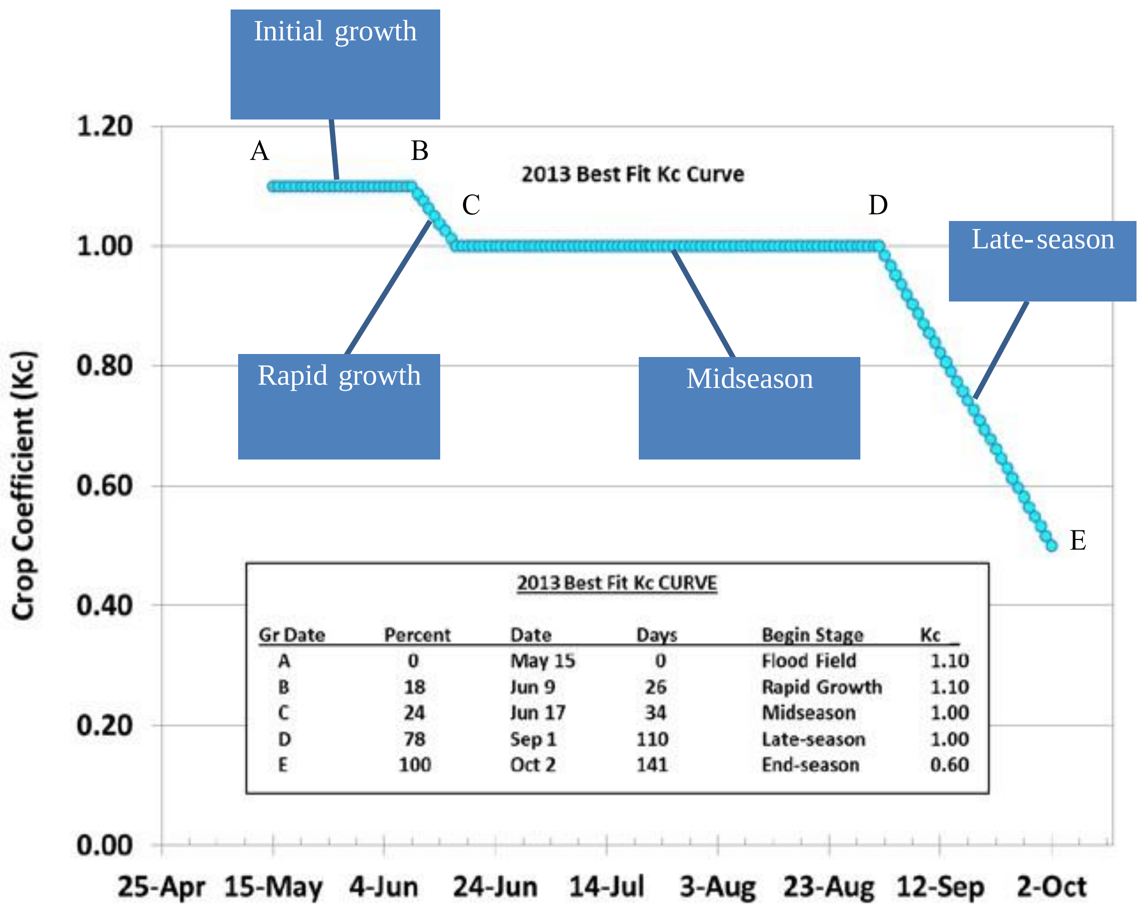
RMSE values for PETc and OETc for each of the experimental fields used from 2011 through 2013 are given in Table 1. The RMSE for all those fields was 0.77 mm d^{-1}. The peak daily ETc rate during this period was approximately 7.0 mm d^{-1}. As a result, the ratio of RMSE to the peak ETc is less than 15 percent, which indicates a very good fit between predicted and observed values. Plots of the daily PETc and OETc for the experiments from 2011 through 2013 are given in Appendix B.

Table 1. Growth Dates, Days in the Season, and RMSE of Daily Predicted versus Observed Crop Evapotranspiration, for each Experimental Field (2011–2013)

Growth Date	North Field 2011	East Field 2011	South Field 2011	North Field 2012	East Field 2012	South Field 2012	North Field 2013	East Field 2013	South Field 2013
A	May 26	May 27	May 27	May 26	May 27	May 27	May 15	May 15	May 15
B	June 21	June 21	June 22	June 22	June 23	June 22	June 7	June 9	June 9
C	June 30	June 29	July 1	July 1	July 2	July 1	June 15	June18	June 18
D	Sept. 18	Sept. 13	Sept. 18	Sept. 23	Sept. 22	Sept. 18	Aug. 25	Sept. 2	Sept. 2
E	Oct. 20	Oct. 14	Oct. 20	Oct. 26	Oct. 25	Oct. 20	Sept. 23	Oct. 3	Oct. 3
Days	**148**	**141**	**147**	**154**	**152**	**147**	**132**	**142**	**142**
RMSE	**0.65**	**0.68**	**0.75**	**0.70**	**0.87**	**0.75**	**0.70**	**0.79**	**0.99**

Note:
RMSE = root mean square error

Figure 3. Best fit Kc Curve based on ETc Measurements from Three Fields per year (2011–2013), and the Mean Growth Stage Dates from the Three Fields (2013)



Note:
ETc = crop evapotranspiration, Kc = crop coefficient

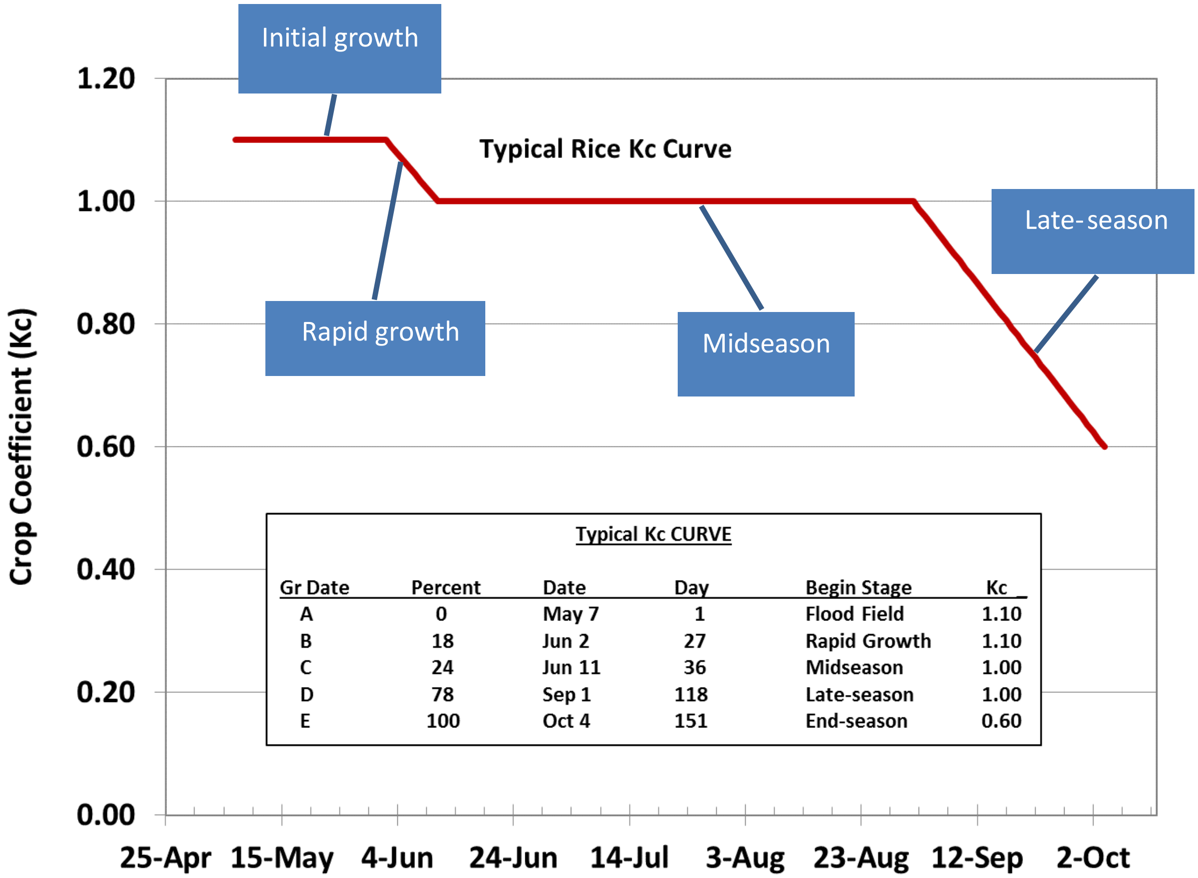
A further test of the Kc curve was obtained by calculating the PCETc and OCETc for each of the experimental plots. The results are shown in Table 2. The RMSE of PCETc versus observed OCETc was 34 mm, with a ratio to the OCETc of 4.6 percent. Using the typical beginning date (May 7) and ending date (October 4) for M206 variety in the Sacramento Valley, and the percentages of the season from A–B (18 percent), A–C (24 percent), and A–D (78 percent), a generalized Kc curve for the Sacramento Valley was derived (Figure 4). The typical beginning and ending dates were recommended by UC Cooperative Extension Farm Advisors and specialists.

Table 2. Comparison of OCETc and PCETc for Each Season, by Year and Location

Year	Location	$OCET_c$	$PCET_c$	Difference	$OCET_c$	$PCET_c$	Difference
		millimeters			inches		
2011	North	711	717	-6	28.0	28.2	-0.2
2011	East	690	703	-13	27.2	27.7	-0.5
2011	South	681	704	-23	26.8	27.7	-0.9
2012	North	759	798	-39	29.9	31.4	-1.5
2012	East	726	794	-68	28.6	31.3	-2.7
2012	South	757	769	-12	29.8	30.3	-0.5
2013	North	762	731	31	30.0	28.8	1.2
2013	East	759	776	-17	29.9	30.6	-0.7
2013	South	813	767	46	32.0	30.2	1.8
Mean		**740**	**751**		**29.1**	**29.6**	
		RMSE = 34 millimeters			**RMSE = 1.3 inches**		
		RMSE / Mean $OCET_c$ = 4.6%			**RMSE / Mean $OCET_c$ = 4.6%**		

Notes:
OCETc = observed cumulative crop evapotranspiration, PCETc = predicted cumulative crop evapotranspiration, RMSE = root mean square error

Figure 4. Typical Rice Kc Curve Derived for the M206 Variety in the Sacramento Valley



Note:
Kc values were derived with the root mean square error approach and typical growth dates for the M2016 rice variety.

3.3. Crop Coefficient Curve Validation

Observations from 2007 through 2009 were also tested using the RMSE to confirm the findings and further validate for the best fit Kc curve developed from 2011–2013 data. The values Kc1 = 1.1, Kc2 = 1.0, and Kc3 = 0.6, and the percentages of the season from A–B (18 percent), A–C (24 percent), and A–D (78 percent) were used to generate the Kc curves for each rice field. The RMSE values for each of the experimental fields from 2007 through 2009 are given in Table 3. The RMSE over all of the data was 1.08 mm d^{-1}. The ratio of the RMSE to the peak ETc was on the order of 15 percent. Results from the 2007–2009 data were not as consistent as that for the 2011–2013 data because of technological and performance improvements for sensors used during the in 2011–2013 field studies. Also, there was considerably less missing data in the latter study because of digital modems being installed at each station location. Additional discussion regarding missing data can be found in Appendix A. Plots of the daily PETc and OETc for the 2007–2009 experiments are given in Appendix C. A further test of the Kc curve was obtained by calculating the PCETc and OCETc for each of the experimental plots. The results are shown in Table 4. The RMSE of PCETc versus OCETc was 50 mm. The ratio of the RMSE to the OCETc was 5.9 percent.

Table 3. Growth Dates, Days in the Season, and RMSE of Daily PETc versus OETc, for each Experimental Plot (2007-2009)

Site	2007–Wet	2007–Drill	2008–Wet	2008–Drill	2009–Wet	2009–Drill
A	May 5	April 27	May 5	May 5	May 16	May 16
B	June 3	May 27	May 30	May 30	June 11	June 11
C	June 13	June 6	June 8	June 8	June 19	June 19
D	Sept. 11	Sept. 4	Aug. 24	Aug. 24	Sept. 6	Sept. 6
E	Oct. 17	Oct. 10	Sept. 24	Sept. 24	Oct. 7	Oct. 7
Days	166	167	143	143	145	145
RMSE	1.05	1.30	0.97	1.00	1.00	1.14
RMSE over all data = 1.08						

Notes:
OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration,
RMSE = root mean square error
In each year, there was one drill-seeded and one wet-seeded experimental field.

Table 4. Comparison of OCETc and PCETc by Year and Experimental Plot

Year	Treatment	OCETc	PCETc	Difference	OCETc	PCETc	Difference
		millimeters			inches		
2007	Wet	813	837	-24	32.0	33.0	-0.9
2007	Drill	873	855	18	34.4	33.7	0.7
2008	Wet	889	842	47	35.0	33.1	1.9
2008	Drill	865	842	23	34.1	33.1	0.9
2009	Wet	856	791	65	33.7	31.1	2.6
2009	Drill	875	791	84	34.4	31.1	3.3
Mean		862	826	36	33.9	32.5	1.4
		RMSE = 50 millimeters			RMSE = 2.0 inches		
		RMSE / Mean OCETc = 5.9%			RMSE / Mean OCETc = 5.9%		

Notes:
OCETc = observed cumulative crop evapotranspiration, PCETc = predicted cumulative crop evapotranspiration,
RMSE = root mean square error

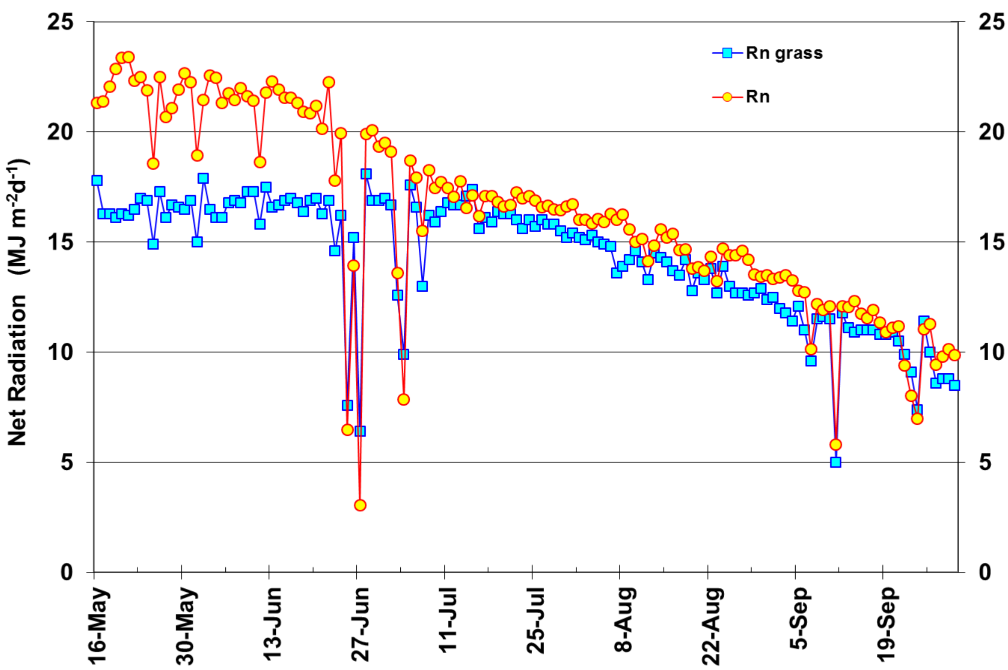
3.4. Crop Coefficients

The Kc values were highest during the initial growth stage (A–B), when the plants shaded less than 10 percent of the surface and the rice fields were mostly flooded. The average Kc = 1.10 was observed for dates A through B. The average Kc for dates C through D was approximately 1.00. This result is unconventional when compared to FAO Kc values reported by Allen et al. (1998), which suggests Kc = 1.00 for dates A through B, and Kc = 1.15 for dates C through D. During the initial growth period, the paddies were mostly covered with water and small plants. During this period, the sensible heat flux measurements from both the sonic anemometer and the surface renewal method were consistently close to zero. There was positive heat storage in the water during the mornings, but most of that stored energy was gradually lost from the water mainly because of evaporation during the afternoon and night. Consequently, the net heat storage in the water was close to zero on a daily basis unless the paddy was drained and refilled. Because daily sensible heat flux and heat storage in the water and soil averaged out to near zero on a daily basis, the high Kc during initial growth is likely caused by differences in net radiation over the flooded paddy and over a grass reference surface.

While albedo was not measured in these experiments, the albedo from still water is approximately 5 percent when the zenith angle from normal to the surface to the sun is less than 45°, and it increases when the sun is lower on the horizon (Monteith and Unsworth 2013). Because the albedo of many cereal crops is on the order of 25 percent, the albedo should increase considerably as the paddy water becomes shaded by the rice plant canopy. That explains the higher Kc value during the initial growth relative to the midseason period.

In an earlier experiment, when the paddy was not flushed, the daily net radiation used to calculate ETo was compared with the observed net radiation over rice (Figure 5). The results indicated that the Rn was considerably higher over the paddy than over the grass during initial growth. The Kc value during initial growth was Kc = 1.20. The difference in Rn decreased during rapid growth of the rice plants, and there was little or no difference in Rn during the midseason (C–D) period. The higher Kc during initial growth is most likely the result of high Rn over water that decreases as the plants grow. There was more flushing of the rice paddies during the 2011–2013 seasons, which likely reduced the Kc from 1.20 to 1.10.

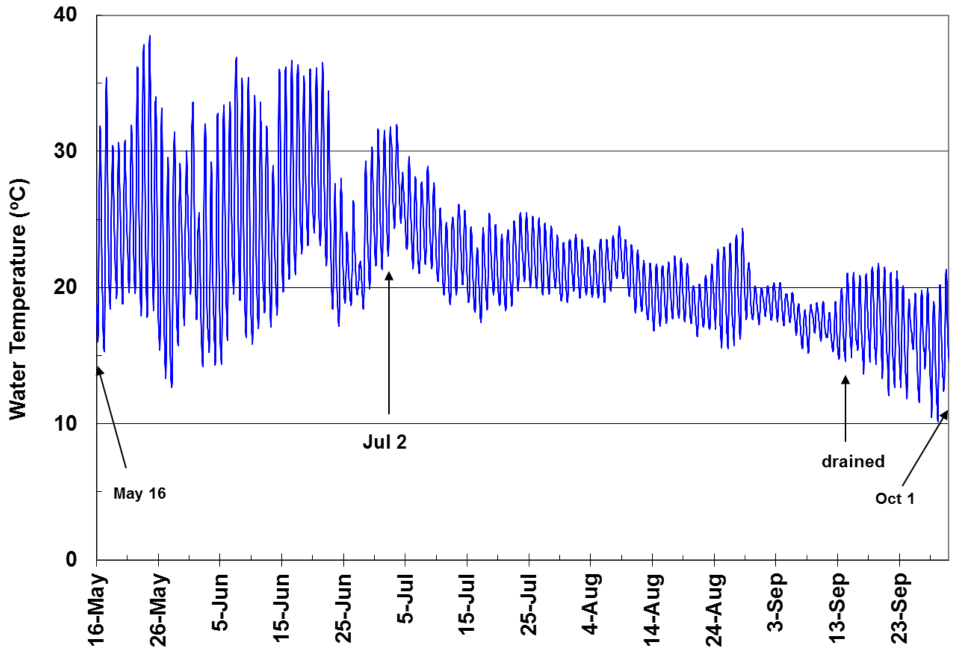
Figure 5. Daily Rn Measured over a Continuously Flooded Rice Paddy near Nicolaus (2000) and the Corresponding Calculated Rn over Grass for Estimating ETo at the Nicolaus CIMIS Station



Note:
CIMIS = California Irrigation Management Information System, ETo = reference evapotranspiration,
Rn = net radiation

The justification for a higher Kc value during dates A through B is also clear in Figure 6, which shows the water temperature measured during the 2000 season. During dates A through B, the mean water temperature and the range of water temperature was considerably higher than observed during midseason, which was approximately between July 2, and just before the field was drained. Note that the rice paddy was continuously flooded during 2000. From 2011 through 2013, most of the fields were flushed one or

Figure 6. **Water Temperature Measured over a Continuously Flooded Rice Paddy near Nicolas (2000)**



more times during dates A through B. The net radiation decreased when the fields were drained. As a result, the Kc values were somewhat lower in the later experiments than in the 2000 experiment.

Using a modification of the daily time step standardized reference evapotranspiration equation for short canopies with a fixed canopy resistance and aerodynamic resistance expressed as an inverse function of the wind speed, there are only three factors that make ETc different from ETo. Those factors are differences in (1) net radiation, (2) canopy resistance caused by crop physiology and surface wetness, and (3) crop morphology, which affects surface roughness and aerodynamic resistance. Using a modification of the Penman-Monteith equation, a crop coefficient can be expressed as:

$$K_c = \frac{\left(\dfrac{0.408\Delta(C_n R_n - G) + \gamma\left(\dfrac{187200}{T+273}\right)\left(\dfrac{u_2}{r_{ac} \cdot u_2}\right)(e_s - e)}{\Delta + \gamma\left(1 + \left(\dfrac{r_{cc}}{r_{ac} \cdot u_2}\right)u_2\right)} \right)}{\left(\dfrac{0.408\Delta(R_n - G) + \gamma\left(\dfrac{187200}{T+273}\right)\left(\dfrac{u_2}{208}\right)(e_s - e)}{\Delta + \gamma\left(1 + \left(\dfrac{70}{208}\right)u_2\right)} \right)} \tag{5}$$

Where Rn, G, and H are all expressed in W m^{-2}. In this equation, the denominator is equivalent to the daily ETo equation (Allen et al. 1998) and the numerator is a modification of the same equation to represent a crop. In Equation 5, Cn is a coefficient to estimate Rn measured over a crop from estimated Rn over the ETo surface. The aerodynamic resistance (ra) for ETo is estimated as ra = $208/u_2$ s m^{-1}, where

u_2 is the wind speed measured at 2 meters over a grass surface, and the canopy resistance (rc) for ETo is rc = 70 s m^{-1}. The aerodynamic resistance of the crop (rac) is given by $(rac \cdot u_2)/u_2$, and the canopy resistance of the crop (rcc), depend on morphology and physiology of the crop. On a daily basis, the G is approximately equal to zero for the ETo, ETc, and for standing water, such as a flooded rice paddy. As a result, the Kc value at any given time depends on the coefficients Cn, rac, and rcc.

For a flooded rice field with less than 10 percent ground shading, the Cn value is typically on the order of 1.20 to 1.30, and the canopy resistance is rcc = 0. But, the aerodynamic resistance is quite high because the surface is smooth and there is nothing to cause turbulence. For an open water surface, the aerodynamic resistance is most likely somewhat higher than $208/u_2$, which is for 12 cm-tall grass. As a result, for a flooded rice field, the higher rac will reduce the transfer of heat and water vapor and should reduce the evaporation to somewhat less than ETo. But, the Rn is considerably higher and the canopy resistance is zero, which greatly increases vaporization and crop evapotranspiration relative to ETo.

During nine years of rice evapotranspiration measurements, including the three years reported in this experiment, the Kc values during initial growth (A–B) were typically on the order of Kc = 1.10. The Kc values tended to be higher when the paddy was continuously flooded, and then decreased whenever the paddies were flushed one or more times for weed management.

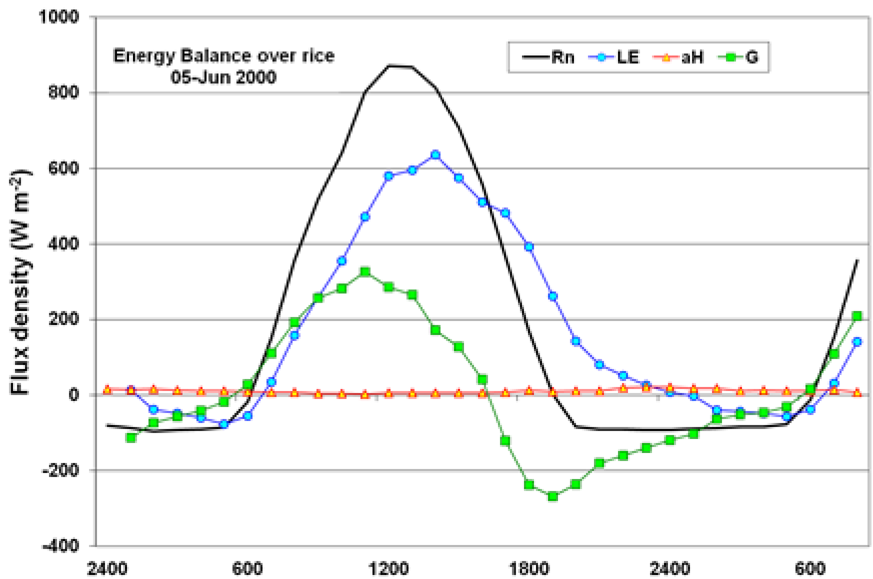
As a rice canopy develops, the Rn decreases because the albedo increases, the canopy resistance increases because of stomatal control of the rice plants, and the aerodynamic resistance decreases because of enhanced turbulence as the surface roughness increases. But, the increased canopy resistance and decreased Rn likely dominate the decreased aerodynamic resistance; especially in a low-wind-speed rice-growing region such as the Sacramento Valley.

During the late season period, the rice canopy tends to open up with a slight decrease in Rn (Figure 5) and an increase in canopy resistance, presumably because of a combination of reduced stomatal conductance and drying of the soil after draining the paddy. As a result, the Kc values gradually decrease during the late season period (D–E).

Some of these concepts are illustrated in Figures 7 and 8. Figure 7 shows the energy balance measured over a flooded rice field on June 5, 2000, when the rice shaded less than 10 percent of the surface. The Rn peaked at approximately 850 watt (W) m^{-2}. The Rn used to calculate ETo peaked at approximately 650 W m^{-2} on the same day. The H was close to zero all day and night mainly because the surface was mostly smooth and there was nothing to cause turbulence. As a result, the aerodynamic resistance was high and it inhibited the transfer of heat and water vapor between the air and the surface. Because of the high Rn, considerable heat was captured in the water, which raised the water temperature (and heat content) considerably during daylight. Late in the afternoon, the Rn dropped, and much of the heat stored in the water came back to the surface and contributed to vaporization, which increased the LE. The LE was quite high during the evening and night as the heat in the water contributed to vaporization.

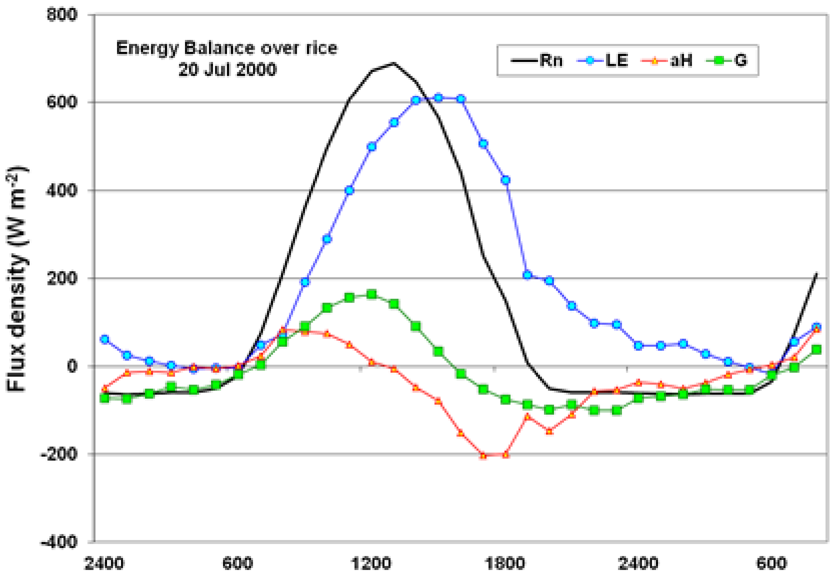
Figure 8 shows the energy balance on July 20, 2000, when the rice canopy was fully developed. The peak Rn dropped from 850 W m^{-2}, which was measured over water on June 5, to approximately 650 W m^{-2} measured over the plant canopy on July 20. This is most likely because of an increase in reflection of solar radiation from the canopy. Note that the peak Rn used to calculate ETo on the same day was about 650 W m^{-2}, so the net radiation over a rice canopy was similar to that of the estimated for the ETo surface (i.e., an irrigated pasture). In Figure 8, note that H is no longer near zero but shows positive, upward flux in the morning, and negative downward flux in the afternoon and nighttime. Because the rice canopy is somewhat rough, it causes turbulence when the wind is blowing, which lowers the aerodynamic resistance. Because the sun shining on the rice canopy in the morning raises the temperature relative to the air temperature above, there will be a positive H from the rice canopy to the air above. In the afternoon, the air has warmed up and the rice canopy is transpiring, so the canopy is cooler than the air above, and the sensible heat transfer is negative, downward from the warmer air to the cooler surface. Also, during the nighttime, the air is warmer than the canopy, so there is a downward sensible heat transfer. There still is morning heat storage in the water as the sun warms the water, but it is considerably less than for the flooded field in Figure 7. Again, as the Rn lowers in the afternoon, heat stored in the water moves upward to the surface to vaporize water during the afternoon and nighttime. As with the flooded rice, the heat storage in the water tends to balance out near zero during the day, as long as the paddy is not flushed. The LE curve for the rice data in Figure 8 is similar to that of ETo under the same weather conditions, except the curve is shifted to the right because heat storage in the water, which reduces ETc during the day, leads to more evaporation, and higher ETc during the evening and night.

Figure 7. Energy Balance Measured over a Flooded Rice Paddy with Less Than 10 Percent Shading by the Rice Canopy



Note:
aH = calibrated sensible heat flux density, G = ground heat flux, LE = latent heat flux, Rn = net radiation

Figure 8. Energy Balance Measured over a Rice Paddy with Greater Than 75 Percent Shading by the Rice Canopy



Note:
aH = calibrated sensible heat flux density, G = ground heat flux, LE = latent heat flux, Rn = net radiation

The FAO papers by Allen et al. (1998) and by Doorenbos and Pruitt (1977) both reported a rice Kc = 1.15 for midseason, but neither paper provide references on how the Kc = 1.15 was derived. Laurence and Pruitt (1971) measured the evapotranspiration of a commercial rice paddy in the Sacramento Valley with the Bowen ratio method and reported a midseason Kc = 1.02. They did not report Kc values during the initial growth period. It is known that the older varieties of rice were considerably taller than the M206 studied in this research; but, the Kc results were quite similar to what was found in these experiments. The midseason Kc values observed for rice in these studies was consistently observed to be approximately Kc = 1.00. While the FAO publications give Kc values on the order of 1.15 to 1.20 for many cereal crops, they do not provide citations that validate those numbers.

Using the high precision lysimeters at UC Davis, and energy flux measurements, the midseason Kc values for maize and cereal crops were found range from approximately 0.95 to 1.05. The only possible reason for differences between midseason Kc values of cereal crops are differences in Rn, rc, and ra. About the same midday, midseason Rn for rice and ETo were observed in these experiments. Canopy resistance might be slightly less for rice than for ETo because of the taller canopy and standing water, but there is no available method to validate this and there is no available research literature on the topic. Aerodynamic resistance is estimated as an inverse function of the wind speed, but summertime wind speeds are generally quite low in the Sacramento Valley, so rac values will tend to be high regardless of the numerator used in the inverse function.

The only apparent measurements of rice evapotranspiration in the Sacramento Valley were reported by Laurence and Pruitt (1971). They found midseason Kc values of approximately 1.00 and 1.05 in the two years they studied. But, they felt that the Kc values should be higher because of the low wind speeds and high humidity near their research field (35 km north of Davis) and the fact that ETo was estimated using the lysimeter in Davis, which was in a windier, drier climate. Also, Clyde Muir (from DWR) reported 28 percent higher evaporation readings from 1-gallon insulated evaporimeters in Davis than the studied rice field. But, no information on siting of those evaporimeters was provided. Many years later, based on CIMIS ETo data recorded in Davis and at the former Nicolaus CIMIS station, which was close to the research site of Laurence and Pruitt, the area of the rice research site had only approximately 5 percent lower ETo than at Davis. Of course, Laurence and Pruitt did not have that information in 1971. Current data logging and net radiation sensors are much improved since 1971, and it is expected that the ETc data today are better than in the past. Based on the facts that (1) the Rn sensors are better, (2) the new rice varieties are shorter, and (3) this study used much improved ETo estimates from CIMIS and Spatial CIMIS rather than ETo from a different climate region, it is quite reasonable to conclude that a Kc = 1.00 is a good estimate for midseason rice in the Sacramento Valley.

3.5. Bare Soil Evaporation

In these experiments, the observed bare soil evaporation was variable. The results from the bare soil experiments are shown in Figures 9, 10, and 11. Observed soil evaporation ranged from 95.8 mm (3.8 inches, or 0.32 foot) in 2012, to 139 mm (5.4 inches, or 0.45 foot) in 2013. The evaporation was likely higher in 2013 because of land leveling, which brings soil moisture to the surface and increased evaporation following the leveling. The average observed soil evaporation for 2012 and 2013 was 117 mm (4.6 inches, or 0.38 foot). Based on the two seasons, 104 mm (4.1 inches, or 0.34 foot) for the season that runs May 1 through September 22, can be considered a low estimate of the bare soil evaporation.

Observations from 2012 and 2013 showed a large variation in bare soil evaporation. A larger sample is needed before a typical value can be recommended. In addition, there is not broad consensus among experts about the application of bare soil evaporation to rice paddy crop evapotranspiration computation. As a result, more study is needed before applying this element of the energy balance with confidence to the rice paddy crop.

Figure 9. Data from the Bare Soil Plot: (a) Daily Precipitation (Pcp) with Observed ETa, (b) Observed and Estimated Daily Evaporation Coefficient (Ka), and (c) Observed and Estimated CETa (2011)

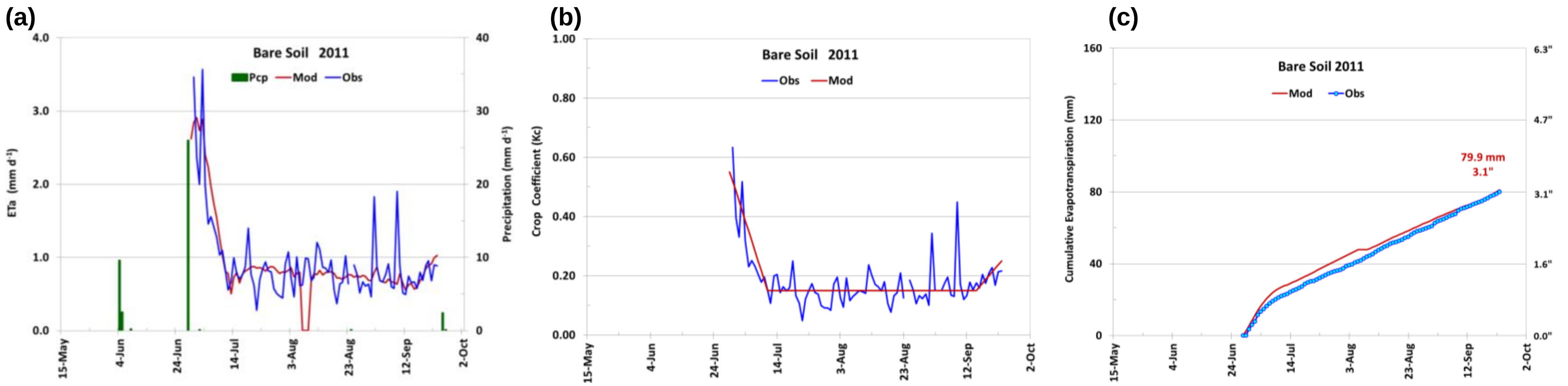


Figure 10. Data from the Bare Soil Plot: (a) Daily Precipitation (Pcp) and Observed Eta, (b) Observed and Estimated Daily Evaporation Coefficient (Ka), and (c) Observed and Estimated CETa (2012)

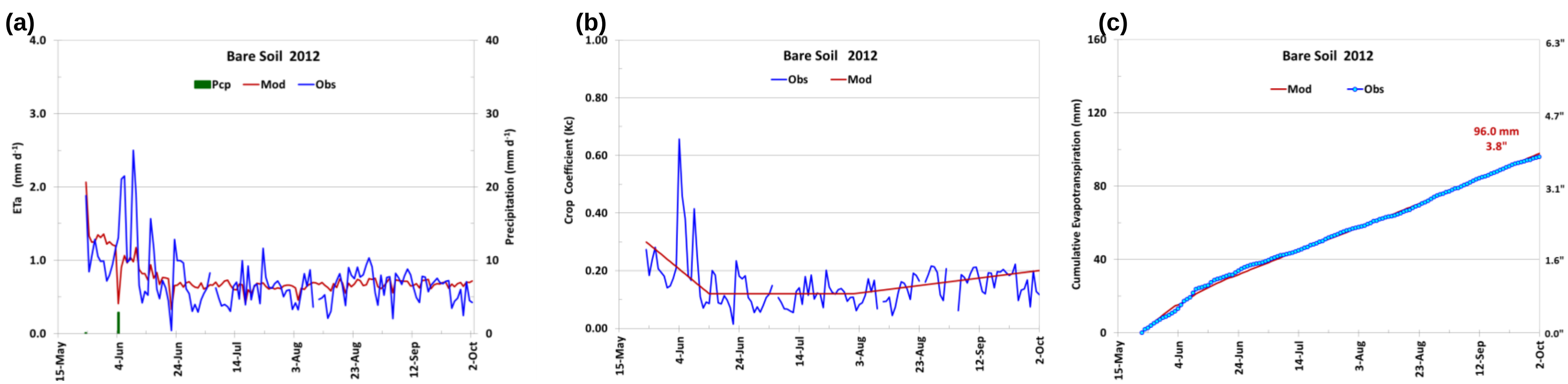
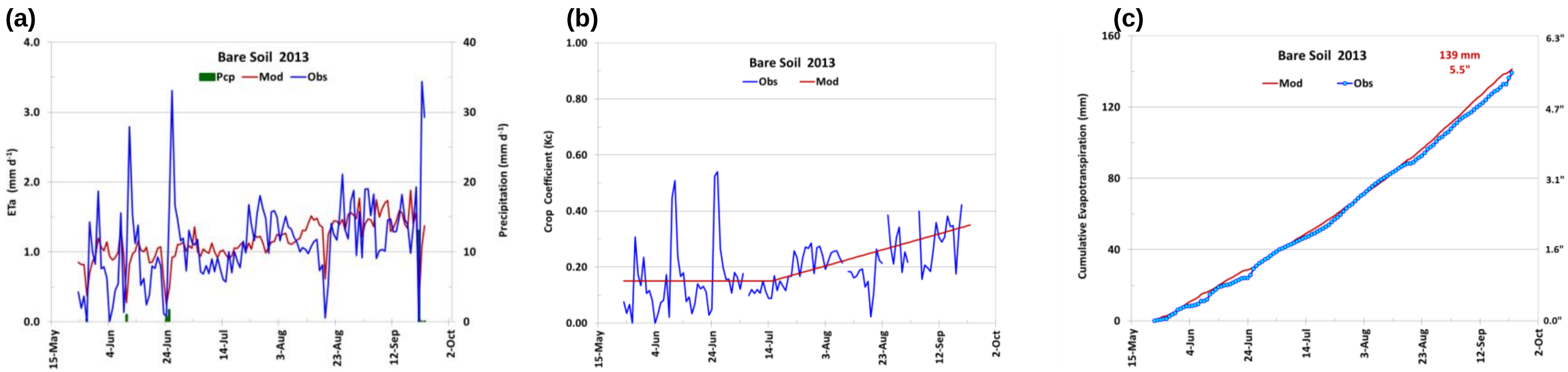


Figure 11. **Data from the Bare Soil Plot: of (a) Daily Precipitation (Pcp) and Observed Eta, (b) Observed and Estimated Daily Evaporation Coefficient (Ka), and (c) Observed and Estimated CETa (2013)**



3.6. Typical Evapotranspiration

For planning purposes, it is useful to have a “typical” ETo and ETc rate for a region of interest. DWR has subdivided California into 482 detailed analysis unit county regions (DAU/counties), which are geographic areas having relatively uniform ETo throughout each of the DAU/counties. The DAUs, which are used for estimating water demand by agricultural crops and other surfaces for water resources planning, are based on watershed and other factors related to water use and movement within a region. The DAUs are often split by counties, so the DAU/counties are the smallest study areas used by DWR. In this section, an estimate of the typical seasonal rice ETc (CETc) for the entire Sacramento Valley is presented. But, in *Improving Rice Water Use Estimates in the Sacramento Valley Based on Updated Crop Coefficients Using DWR’s Cal-SIMETAW Model* (California Department of Water Resources, in prep.), the typical Kc curve is used with ETo rates specific to each DAU/county to provide the ETo and ETc information by DAU/county.

On average, in the Cal-SIMETAW analysis, the computed CETc for rice was 873 mm (34.4 inches, or 2.9 feet) and is a conservative approximation of CETc for rice in the Sacramento Valley for general planning, recognizing that ETo and ETc will vary by DAU/county.

3.7. Relationship of Latent Heat Flux and Net Radiation

Field measurements revealed a high correlation between ETc and available energy (Rn minus water and ground heat storage) on both an hourly and a daily time scale. Rn, which is the main source of energy for evaporation, decreased as the canopy developed and the albedo from the surface increased. As a result, the energy available for evaporation decreased as the canopy grew.

Study results indicate a strong correlation between LE and Rn. Using data collected from the nine fields from 2011 through 2013, the mean of the slopes of a regression of the LE versus the Rn through the origin was b = 0.95. The mean coefficient of determination was $R^2 = 0.88$ (Table 5). About 88 percent of the latent heat flux can be explained by using the equation LE = 0.95·Rn. The remainder of the variation in latent heat flux is likely the result of other factors (e.g., wind, air temperature, water temperature, etc.). ETc, in millimeters per day, is equal to LE (MJ $m^{-2}d^{-1}$) divided by 2.45 MJ kg^{-1}.

3.8. Relationship of Length of Season and Crop Evapotranspiration

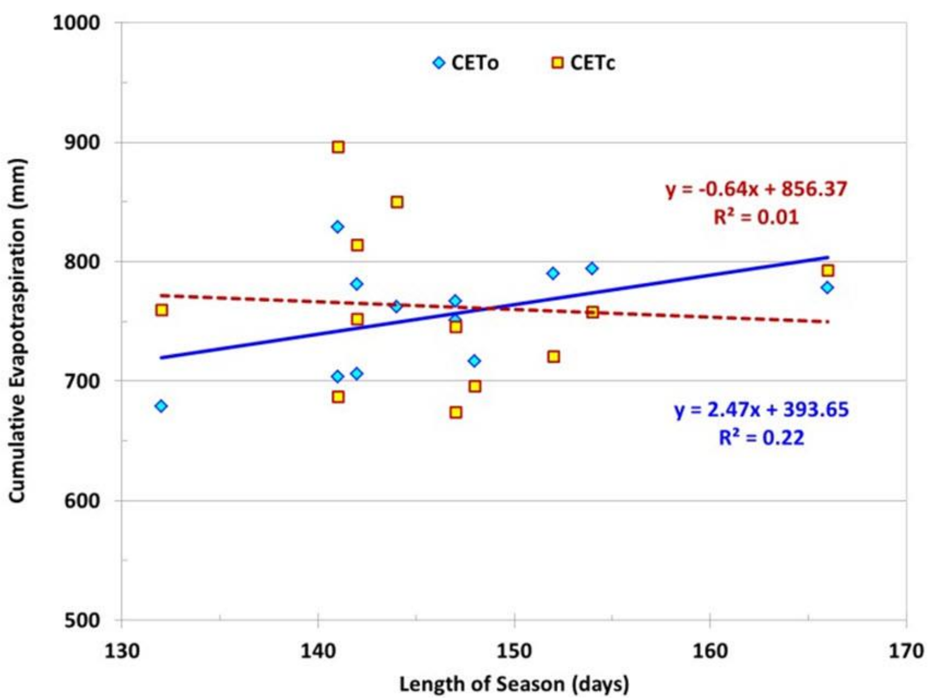
Length of season was not a predictor of seasonal evapotranspiration in these studies. As shown in Figure 12, as the season length increases, there is not a corresponding increase in evapotranspiration. Figures 12 and 13 were developed using data from the wet-seeded rice from 2007 through 2009, and all data from 2011 through 2013. Also, there was no clear relationship between CETc and ETo. There was some indication that seasonal evapotranspiration is higher for rice that is planted earlier (Figure 13). This should be interpreted cautiously, because the earlier experiments in this analysis used a different, less reliable Rn sensor than the later experiments.

Table 5. Slopes and Coefficients of Determination for the Linear Regression Through the Origin of Daily Latent Heat Flux versus Net Radiation for Nine Rice Fields (2011–2013)

Year	Location	Slope	R^2
2011	North	0.94	0.94
	East	0.94	0.89
	South	0.93	0.93
2012	North	0.97	0.91
	East[a]	0.96	0.85
	South	0.95	0.91
2013	North	0.95	0.82
	East	0.94	0.86
	South	0.95	0.85
	Mean	**0.95**	**0.88**

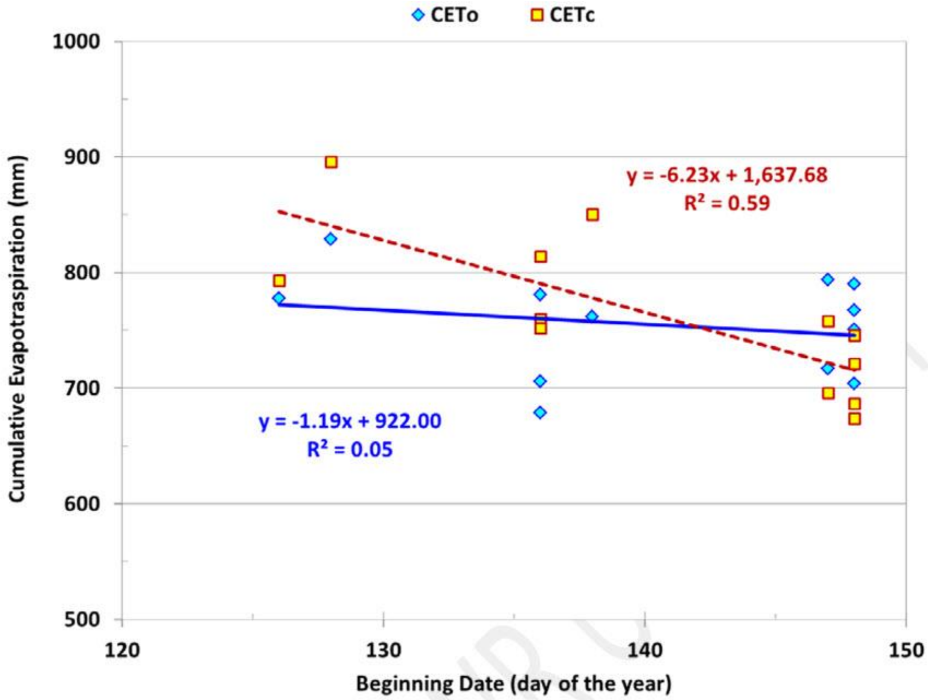
Notes:
R^2 = coefficients of determination
[a]Data were missing for the first 20 days in 2012.

Figure 12. Observed Cumulative Seasonal Evapotranspiration Based on the Length of the Season



Note:
CETc = cumulative crop evapotranspiration, CETo = observed crop evapotranspiration, R^2 = coefficients of determination

Figure 13. Cumulative Seasonal Evapotranspiration Based on the Season Beginning Date



Note:
CETc = cumulative crop evapotranspiration, CETo = observed crop evapotranspiration, mm = millimeters, R^2 = coefficients of determination

3.9. Relationship of Water Temperature and Crop Evapotranspiration

The influence of water temperature on rice ETc was also investigated. Findings indicate little or no evidence that water temperature affects the ETc rates in these experiments. Before the canopy developed, the daily fluctuations in water temperature were large. They decreased to quite small fluctuations once the full canopy developed. In addition, there is a wide range of management practices related to flushing the fields that were not analyzed in this study. But, the study results do show that there was no significant difference in evapotranspiration related to use of drill seeding or wet seeding, as evaluated in previous studies from 2007 to 2010.

3.10. Evapotranspiration of Applied Water

Traditionally, for a well-drained soil, DWR estimates ETaw as the seasonal cumulative evapotranspiration (CETc) minus effective rainfall (Pe) and the decrease in soil water content (ΔSW) during the season:

$$ETaw = CETc - Pe - \Delta SW \quad (6)$$

Because soils are usually either covered by water or fully saturated by flooding, the standard approach for calculating ETaw was not used in this study. Using the typical Kc curve presented in this research, and the mean daily ETo from the Colusa CIMIS station, the seasonal M206 rice evapotranspiration is CETc = 863.6 mm (34.0 inches). During the rice growing season in the Sacramento Valley, it is reasonable to assume that effective rainfall is negligible, so Pe $\approx$ 0. Once the rice paddy is flooded, any evaporation that occurs is a contributor to ET and is not considered to be ETaw because there is no significant soil moisture loss from none-saturated soils. In addition, any water that was stored in the soil prior to flooding the paddy that contributes to evaporation is not considered as part of the ETaw equation. Therefore, any soil evaporation that might occur from the bare soil if the paddy was not flooded does not come from the developed supply (i.e., it is not applied water). As a result, the ΔSW used in Equation 6 can be estimated as the seasonal cumulative bare soil evaporation (CE) expected if the paddy was not flooded. For an unirrigated, bare soil, the crop transpiration is zero and the seasonal ΔSW is equal to the cumulative soil evaporation from June through September in the Sacramento Valley:

$$\Delta SW \approx CE \qquad (7)$$

In these studies, bare-soil evaporation was measured during the three seasons to obtain an estimate of ΔSW. While the field research attempted to quantify bare-soil evaporation effects, the results were confounded in some years by rainfall and management practices. Based on the three years of data collection, a conservative estimate for the bare-soil evaporation from May 1 through September 22 averaged approximately 0.7 mm per day, for a total of approximately 0.34 foot (4.1 inches) during the season. As a result, ΔSW = E = 4.1 inches could be considered a reasonable estimate of soil moisture loss from fallowed fields until new information is developed.

4. Conclusions

Based on evapotranspiration data collected from nine paddy rice fields from three station locations, during three years, a typical rice Kc curve was derived for M206 rice grown in the Sacramento Valley (Figure 3). Percentages of the season to the end of each growth period shown on Figure 3 can be used to adjust this typical Kc curve for variations in first flooding and end date in other years. The Kc values for the various growth periods developed for the M206 variety can be used as an approximation for other rice varieties, provided that growth dates are adjusted in accordance with the characteristics of the variety.

The differences in rice evapotranspiration around the Sacramento Valley appear to be mainly related to spatial variation in ETo. Using the typical rice Kc curve, which adjusts for planting and ending dates, with the local ETo, should provide good estimates of rice evapotranspiration throughout the valley.

The length of the season and the water temperature were not reliable predictors of seasonal CETc in these studies. There was some indication that seasonal evapotranspiration is higher for crops that are planted earlier (Figure 13). This should be interpreted cautiously because the earlier experiments in this analysis used a different, less reliable, Rn sensor than the later experiments.

Using the Kc curve developed in this study, and historic mean daily ETo rates from Colusa, the average seasonal ETc from1986 through 2010, was computed to be 863.6 mm (34.0 inches, or 2.8 feet). Results from these experiments indicate that the bare soil evaporation was approximately 0.7 mm per day, for a total of approximately 0.34 foot (4.1 inches) during the entire season.

References

Allen RG, Pereira LS, Raes D, and Smith M. 1998. *Crop evapotranspiration: Guidelines for computing crop water requirements*. Irrigation and Drainage Paper No. 56, Food and Agricultural Organization of United Nations, Rome.

Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder RL, Itenfisu D, Steduto P, Berengena J, Baselga Yrisarry J, Smith M, Pereira LS, Raes D, Perrier A, Alves I, Walter I, Elliott R. 2006. A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. Agricultural Water Manual, 81: 1–22.

California Department of Water Resources. 1986. *Bulletin 113-3, Crop Water Use in California*. Sacramento, CA.

California Department of Water Resources. 1998. *Bulletin 160-88, California Water Plan Update*. Sacramento, CA.

California Department of Water Resources. In prep. *Improving Rice Water Use Estimates in the Sacramento Valley Based on Updated Crop Coefficients Using DWR's Cal-*SIMETAW *Model.* Sacramento, CA.

Chen W, Novak MD, Black TA. 1997. "Coherent eddies and temperature structure functions for three contrasting surfaces. Part I: Renewal model for sensible heat flux." Boundary-Layer Meteorology Volume 84:125–147.

de Vries DA. 1963. "Thermal properties of soils." Physics of Plant Environment, pp. 210–235. Amsterdam, The Netherlands: North-Holland Publishing Company.

Doorenbos J, Pruitt, W O. 1977. *Crop water requirements*. Irrigation and Drainage Paper No. 24, Food and Agricultural Organization of United Nations. Rome.

Hart QJ, Brugnach M, Temesgen B, Rueda C, Ustin S L, Frame K. 2009. "Daily reference evapotranspiration for California using satellite imagery and weather station measurement interpolation." Civil Engineering and Environmental Systems, 26: 19–33.

Laurence, FJ, Pruitt WO. 1971. "Energy balance and water use of rice grown in the Central Valley of California." Agronomy Journal Volume 63: 827–832.

Lee X, Massman WJ, Law BE (eds.). 2004. Handbook of micrometeorology: A guide for surface flux measurement and analysis. Kluwer. Academic Publishers, London, U.K., pp. 250.

Paw U KT, and Brunet Y, 1991. "A surface renewal measure of sensible heat flux density." Proclamation of the 20th Conference on Agriculture and Forest Meteorology, Salt Lake City, pp. 52–53.

Paw U KT, Qiu J, Su HB, Watanabe T, and Brunet Y. 1995. "Surface renewal analysis: a new method to obtain scalar fluxes without velocity data." Agricultural and Forest Meteorology Volume 74: 119–137.

Paw U KT, Snyder RL, Spano D, and Su HB. 2005. “Surface renewal estimates of scalar exchange.” Micrometeorology in Agricultural Systems. Hatfield JL and Baker JM (eds.). ASA Monograph No. 47, ASA-CSSA-SSSA, Madison, WI. ISBN 0-89118-158-X. pp. 455-483.

Shapland, TM, McElrone AJ, Paw U KT, and Snyder RL. 2013. A turnkey data logger program for field-scale energy flux density measurements using eddy covariance and surface renewal. Italian Journal of Agrometeorology January 2013.

Shaw RH, and Snyder RL. 2003. “Evaporation and eddy covariance.” Encyclopedia of Water Science. Stewart BA, and Howell, T (eds.). Marcel Dekker Inc., New York. DOI: 10.1081/E-EWS 120010306.

Snyder RL, Spano D., and Paw U K.T., 1996. “Surface renewal analysis for sensible and latent heat flux density.” Boundary-Layer Meteorology Volume 77: 249–266.

Spano D, Snyder RL, Duce P, and Paw U KT. 1997. “Surface renewal analysis for sensible heat flux density using structure functions.” Agricultural and Forest Meteorology Volume 86: 259–271.

Spano D, Snyder RL, Duce P, Paw U KT. 2000. “Estimating sensible and latent heat flux densities from grapevine canopies using surface renewal.” Agricultural and Forest Meteorology Volume 104:171–183.

Stoy PC, Mauder M, Foken T, Marcolla B, Boeghe E, Ibromf A, Araing MA, Arneth A, Aurelai M, Bernhoferj C, Cescattik A, Dellwik E, Duce P, Gianelled D, van Gorsel D, Kiely G, Knohl A, Margolis H, McCaughey H, Merbold L, Montagnani L, Papale D, Reichstein M, Saunders M, Serrano-Ortiz P, Sottocornola M, Spano D, Vaccarim F, Varlagin A. 2013. “A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity.” Agricultural and Forest Meteorology Volumes 171–172: 137–152.

Van Atta CW. 1977. “Effect of coherent structures on structure functions of temperature in the atmospheric boundary layer.” Archives of Mechanics Volume 29:161–171.

Webb EK, Pearman GI, and Leuning R. 1980. “Correction of flux measurements for density effects due to heat and water vapour transfer.” Quarterly Journal of the Royal Meteorological Society Volume 106:85–100.

Appendix A. Methods and Materials

Computation of Reference Evapotranspiration

A crop coefficient (Kc), is the ratio of crop evapotranspiration (ETc) to reference evapotranspiration (ETo):

$$\mathrm{Kc} = \frac{\mathrm{ETc}}{\mathrm{ETo}} \qquad \text{(A1)}$$

The crop coefficient can be applied to estimate ETc for the same crop grown under similar environmental conditions as the ETo:

$$\mathrm{ETc} = \mathrm{Kc\ x\ ETo} \qquad \text{(A2)}$$

ETo is commonly estimated using one of several equations available in the literature and weather data collected over a broad expanse of irrigated grass. ETc is measured using a lysimeter, or with micrometeorological methods.

ETo, is a measure of evaporative demand of the atmosphere. In these field studies, ETo was approximated using the standardized Penman-Monteith equation for short canopies, assuming a canopy resistance of 50 s m^{-1} during daytime and 200 s m^{-1} during the night. Because there are different canopy resistances during daylight and nighttime, there are two hourly equations:

Daytime:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{37}{T+273}\right)u_2(e_s - e)}{\Delta + \gamma(1 + 0.24u_2)} \qquad \text{(A3)}$$

Nighttime

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{37}{T+273}\right)u_2(e_s - e)}{\Delta + \gamma(1 + 0.96u_2)} \qquad \text{(A4)}$$

where ETo is the standardized reference evapotranspiration (mm h^{-1}), Rn is the net radiation (MJ m-2h^{-1}), G is the ground heat flux (MJ m-2h^{-1}), T is the air temperature (°C), u_2 is the wind speed measured at 2 m height (m s^{-1}), e_s (kPA) is the saturation vapor pressure, e(kPa) is the actual vapor pressure, Δ (kPa K^{-1})is the slope of the saturation vapor pressure curve at the air temperature, and γ (kPa K^{-1}) is the psychrometric constant. Derivation of parameters in the hourly ETo equations are presented in Allen et al. (2006). Note that the daily ETo values were determined as the sum of the 24 hourly ETo calculations, and that the daily ETc values were calculated from the sum of 48 half-hourly latent heat flux density (LE) measurements. The daily ETo and ETc values were used to compute the Kc values that were employed to determine the typical Kc curve.

While not directly part of this report, the California Simulation of Evapotranspiration of Applied Water (Cal-SIMETAW) model will be used to account for spatial variability of ETo rates across the Sacramento

Valley to obtain a more accurate spatial estimation of rice ETc. The Cal-SIMETAW model is a computer application that is used to compute ETo, ETc, and ETaw within all of the detailed analysis units (DAUs)/county combinations within California. In Cal-SIMETAW, a daily, rather than an hourly, standardized reference evapotranspiration equation is used to compute ETo (mm d^{-1}):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_s - e)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{(A5)}$$

where Rn is net radiation (MJ $m^{-2}d^{-1}$), G is the ground heat flux (MJ $m^{-2}d^{-1}$), T is the mean daily air temperature (°C), u_2 is the mean daily wind speed (m s^{-1}), e_s(kPa) is the saturation vapor pressure, e (kPa) is the actual vapor pressure, Δ (kPa K^{-1}) is the slope of the saturation vapor pressure curve at the mean daily air temperature, and γ (kPa K^{-1}) is the psychrometric constant derivation of the parameters in the daily standardized reference evapotranspiration equation presented in Allen et al. (2006). While there is some difference in the results from calculated daily ETo and 24-hour sums of hourly ETo in some climates, mainly where there are big differences in daytime and nighttime wind speed and cloudiness, the differences are small during the rice growing season in the Sacramento Valley, where skies are mostly clear and wind speeds are generally low.

Measuring Crop Evapotranspiration

Residual of the Energy Balance

In this research, ETc was measured using the residual of the energy balance method, as follows:

$$\mathrm{ETc} = \frac{\mathrm{LE}}{\mathrm{L}} \quad \text{(A6)}$$

for ETc in kg $m^{-2}d^{-1}$ or mm d^{-1}, LE in MJ $m^{-2}d^{-1}$, and L = 2.45 MJ kg^{-1} is the latent heat of vaporization. The LE was estimated as:

$$\mathrm{LE} = \mathrm{Rn} - \mathrm{G} - \mathrm{H} \quad \text{(A7)}$$

where Rn is net radiation, G is ground heat flux, and H is sensible heat flux.

Measuring Net Radiation

From 2007 through 2009, net radiation was measured using a REBS, Inc., Q7.2 Fritschen net radiometer (Figure A2) set at approximately 2.0 m above the ground. From 2011 through 2013, the NR Lite Net Radiometer from Kipp & Zonen (Figure A3) was used to measure net radiation. While the REBS net radiometers work well, they demand considerable maintenance because of condensation and damage to the plastic domes that protect the thermopile sensor. Many of the maintenance problems were removed by switching to the NR Lite sensor.

Determining Sensible Heat Flux Density

Both the eddy covariance and surface renewal methods (Paw U et al. 1995) were used to estimate H for the latent heat flux density calculations. These methods are based on independent variables/different data/independent parameters and were both used as a check. The surface renewal method is described in Paw U and Brunet (1991), Paw U et al. (1995), Snyder et al. (1996), Spano et al. (1997), and Paw U et al. (2005). Measuring sensible heat flux with a sonic anemometer is described in Shaw and Snyder (2003).

Eddy Covariance

The eddy covariance estimates of H were determined using an RM Young Inc. Model 81000RE tri-dimensional sonic anemometer (Figure A8). Sonic anemometer data were collected at 10 Hz and analyzed following Lee et al. (2004) using half-hourly calculation intervals. The high-frequency wind velocities from the sonic anemometer were rotated into the natural wind coordinate system using the first and second rotation algorithms. H was calculated from the product of the air density, the specific heat of air, and the covariance of the vertical wind and the virtual sonic temperature. The Webb, Pearman, and Leuning density correction terms were applied to the sensible heat flux densities (Webb et al. 1980).

$$H = \rho_a C_p \overline{W'T'} \tag{A8}$$

where ρ_a is the air density, C_p is the specific heat at constant pressure, W' is the fluctuation of the vertical wind speed about its mean, and T' is the fluctuation of the air temperature about its mean. The overbar indicates that the equation uses the mean of the cross products during the 30-minute sampling interval.

Surface Renewal

The surface renewal method was also used to estimate H. The surface renewal method has the advantage of being considerably less expensive, and easier to set up and use, than the eddy covariance method. The only sensor needed for surface renewal is a fine-wire thermocouple (Figure A9). In this research, a 76.2 µm diameter chromel-constantan thermocouple was used to measure high-frequency temperature and to estimate H following the van Atta (1977) approach described in the literature (Paw U et al. 1995, Snyder et al. 1996, Spano et al. 1997, Chen et al. 1997, Spano et al. 2000, Paw U et al. 2005). The high-frequency temperature data were collected at 10 Hz. A time lag of 0.5 second was used to compute uncalibrated half-hourly surface renewal sensible heat flux density (H') using a modified version of the van Atta (1977) structure function. The modified version of van Atta is described in Shapland et al. (2013). The modification was unavailable during the project, but all data collected prior to 2013 were reanalyzed using the Shapland modification of the van Atta function. This decreased the number of missing half-hourly data that are often observed during stable atmospheric conditions. After obtaining the half-hourly H'data, a calibration (α) factor was determined by computing the slope through the origin of H from eddy covariance versus H' from surface renewal. Finally, the calibrated surface renewal value for H was estimated as $H = \alpha H'$. The eddy covariance H was preferentially used over the surface renewal H. When the eddy covariance data were missing, then the surface renewal $\alpha H'$ was used. The advantage from using both the eddy covariance and surface renewal methods is that they are independent and similar results provide a high level of confidence that the data are correct.

Determining Ground and Water Heat Storage

Soil and water heat storage and fluxes were measured with one REBS HFT3 heat flux plate (Figure A4) inserted at 0.05 cm depth below the soil surface. Soil and water temperatures were measured at three depths above the heat flux plates using 107 thermistor (temperature) probes from Campbell Scientific, Inc. The first thermistor was inserted horizontally at approximately 2.5 cm below the soil surface. The other two thermistors were mounted on a length of PVC pipe with a hinge on the bottom (Figure A5). A floating device was attached to the top of the PVC pipe, and the combination of the hinge and float allowed the pipe and sensors to move up and down with the water level. This allowed the soil and water temperatures to always be recorded just below the soil surface, just under the water level of the surface, and midway between the two. A Global Water Instrumentation, Inc. WL400 water level recorder (Figure A6) was used to determine the depth of water above the ground and the volume of water per unit surface area.

In 2013, the setup for the water-level recorder was changed because sunlight was destroying the plastic cover on the cable of the water-level recorder. There was no obvious effect on the water-level data. To solve this problem, the water-level recorder and cable were laid on the ground, and the tip of the water-level recorder was place inside a horizontal PVC pipe that was staked to the ground (Figure A7). In some cases, instrumentation problems resulted in missing data for limited periods of time. For short periods, less than three hours, critical missing data were estimated using a linear trend between observed points. Short periods of missing data occurred mainly at night because of weak battery problems. Because ETc rates are low at night, a linear interpolation provided a reasonable estimate during short data gaps. In a few cases, data were missing for most of the night. In those instances, data from the previous night were used if there was no reason to expect changes. Some records were missing data for several days at the beginning of the experiment because of faulty sensors or late delivery of instrumentation. There were missing data at the end of some experiments because of the grower requesting the stations be removed.

Rice Paddies

Whenever the water level was 0.005 m or less, the ground heat storage was computed using the method of de Vries (1963), where $G = G_2 + \Delta S$. G_2 is the plate measured heat flux at 0.05 m depth and ΔS, (i.e., the change in heat storage in the soil layer above the heat flux plate), is calculated as:

$$\Delta S = 0.05(\mathrm{T_f} - \mathrm{T_i})(0.867\rho_\mathrm{d} + 4.19\theta_\mathrm{v}) \cdot \left(\frac{10^6}{1800}\right) \tag{A9}$$

using a typical soil bulk density ρ_d = 1.4 Mg m^{-3} for a heavy clay soil and a volumetric water content θ_v = 0.27. T_f and T_i are the final and initial half-hour temperatures measured at 0.025 m depth in the soil.

Whenever the water depth was greater than 0.005 m, heat storage in the water and the soil was computed to determine ΔS. The initial and final soil and water temperatures were calculated as the mean of the thermistor temperatures at two heights within water and at the 0.025 m depth in the soil recorded at the beginning and end of a half-hour period. The volume of the soil and water was set equal to the sum of the water depth and 0.05 m of soil. For simplicity, the volumetric heat capacity of water Cv = 4.19 MJ m^{-3}K^{-1} was used in the following equation to estimate ΔS for a flooded rice field:

$$\Delta S = (W_L + 0.05)(\mathrm{T_f} - \mathrm{T_i})(0.867\rho_\mathrm{d} + 4.19\theta_\mathrm{v}) \cdot \left(\frac{10^6}{1800}\right) \tag{A10}$$

using a typical soil bulk density ρ_d = 1.4 Mg m^{-3} for a heavy clay soil and a volumetric water content θ_v = 1.0.

Bare Soil

For bare-soil measurements, the ground heat flux (G) at the soil surface was calculated as the sum of the heat flux plate measurements at 0.05 m depth and the change in heat storage in the soil layer above the flux plate: $G = G_2 + \Delta S$, where G_2 is the average measurement from two heat flux plates installed at 0.05 m depth. The ΔS was determined using the continuity equation and the change in temperature during a half-hour period, following the method of de Vries (1963). The soil heat storage was calculated using:

$$\Delta S = 0.05(\mathrm{T_f} - \mathrm{T_i})(0.867\rho_\mathrm{d} + 4.19\theta_\mathrm{v}) \cdot \left(\frac{10^6}{1800}\right) \qquad \text{(A11)}$$

where $\rho_d = 1.4$ is the soil bulk density, $\theta v = 0.20$ is an estimate of the volumetric water content, and $T_f - T_i$ is the final soil temperature minus initial soil temperature during a half-hour sampling period.

Data Quality

In the experiments from 2007 through 2009, stations were paired to compare wet-seeded with drill-seeded rice ETc, so a few missing data were substituted from the nearby field if the two fields were in similar conditions. For the 2007–2009 data, there were 130 days of missing data out of 904 days (14 percent). Most missing data were at the end of the season when the ETo rates were low. There were more missing data in the 2007–2009 experiments than in the 2011–2013 experiments because there were more problems with the net radiation sensors. The net radiation sensors were changed from REBS Q7.2 Fritschen, to Kipp & Zonen NR Lite in the 2011–2013 experiments. While the REBS net radiometers from the 2007–2009 study worked well, they demanded considerable maintenance because of condensation and damage to the plastic domes that protect the thermopile sensor. Many of the maintenance problems were removed by switching to the NR Lite sensor in 2011. During the entire experiment, there were only five days of missing data from the 2012 east experimental field.

Field Location Details

Locations of the studied rice paddies are provided in Table A1 by year. For the 2007–2009 studies, one field was drill-seeded and the other was wet-seeded by airplane. In 2007, the trial was conducted in adjacent rice fields north of Gridley Road-Colusa Highway about 2 km west of the Sacramento River (north-northeast of Colusa). The experimental fields were located in the same paddies about 5 km east of Maxwell in 2008 and 2009. In 2011 and 2012, the east experimental field was located 0.8 km west of the south end of the Thermalito Afterbay (4.5 km north-northeast of Biggs). In 2013, the experimental field was moved approximately 4.5 km north, to a field just south of the Richvale Highway (4 km east of Richvale).

In 2011 and 2012, the north field was located just east of County Road Z about 5 km north of State Route 162. The intersection of County Road Z and State Route 162 is 5.25 km east of Butte City. In 2013, the north station was moved to a field 7.4 km north-northeast of Nelson. The south experimental field was located 4.25 km northeast of Williams (about 2.5 km south of State Route 20). Evapotranspiration was also measured over bare soil at the Rice Experiment Station near Biggs during the summers of 2011 through 2013. The rice variety grown in all of the experiments was M206.

Table A1. Rice Field Location Information

Number	Experimental Site	Nearby Town	Latitude	Longitude	Elevation (MASL)
1	2007 (Drill and Wet)[a]	Princeton	N39°22′11.0″	W121°55′12.0″	19.8
2	2008 (Drill and Wet)[b]	Maxwell	N39°15′47.5″	W122°07′55.0″	18.3
3	2009 (Drill and Wet)[c]	Maxwell	N39°15′47.5″	W122°07′55.0″	18.3
4	2011-2012 East	Biggs	N39°26′46.6″	W121°42′25.1″	25.0
5	2013 East	Richvale	N39°29′33.0″	W121°41′52.0″	35.7
6	2011-2012 North	Butte City	N39°30′32.0″	W121°55′21.7″	31.7
7	2013 North	Nelson	N39°36′58.7″	W121°44′25.5″	45.4
8	2011-2013 South	Williams	N39°10′11.4″	W122°06′10.1″	14.3
9	2011-2013 Dry Rice (RES)	Biggs	N39°27′26.7″	W121°44′46.2″	25.0

Notes:

MASL = meters above mean sea level, RES = Rice Experiment Station

[a]Northwest field (drill) and southeast field (wet).

[b]North field (drill) and south field (wet).

[c] South field (drill) and north field (wet).

Appendix A Figures

Figure A1. Locations of Experimental Fields

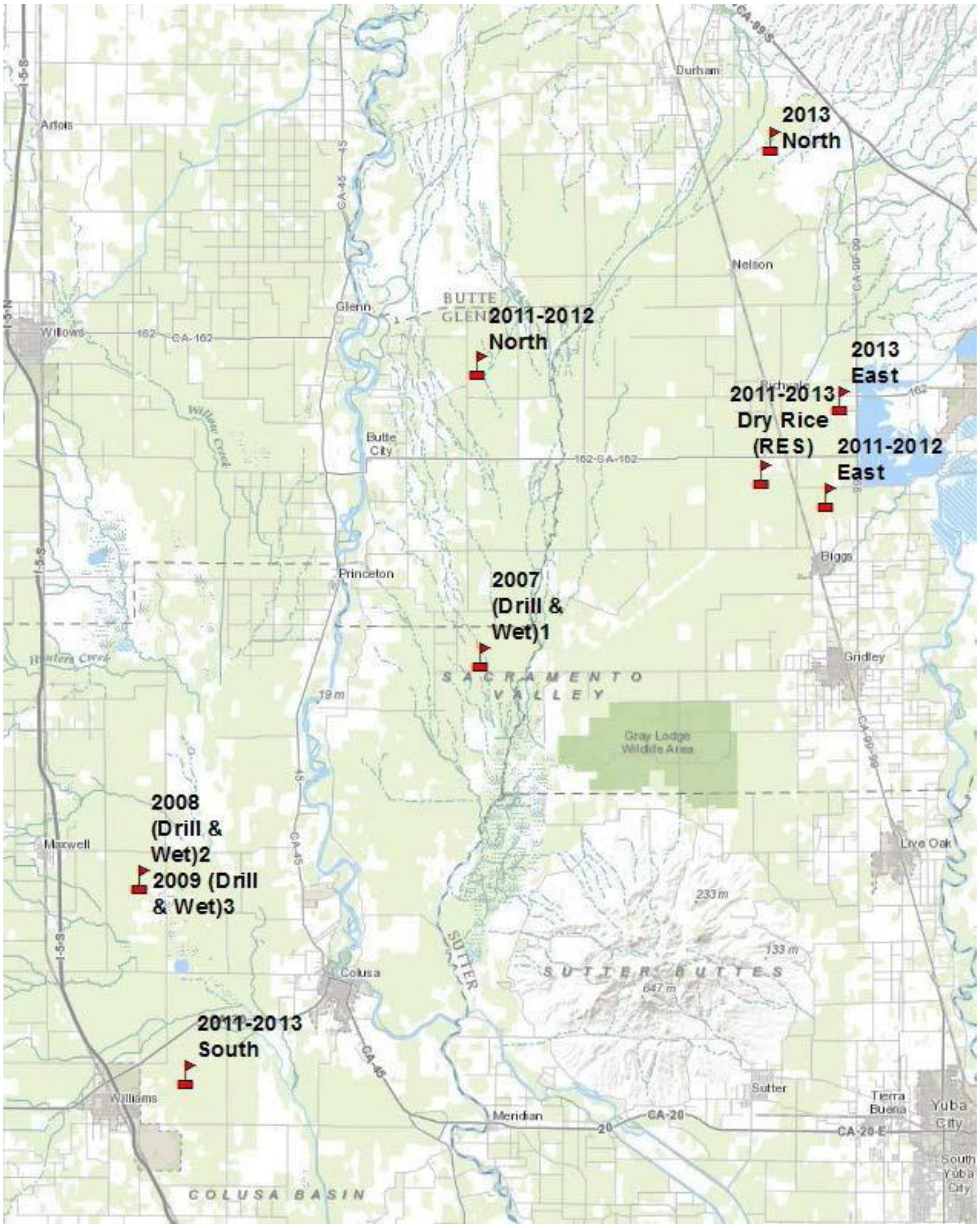


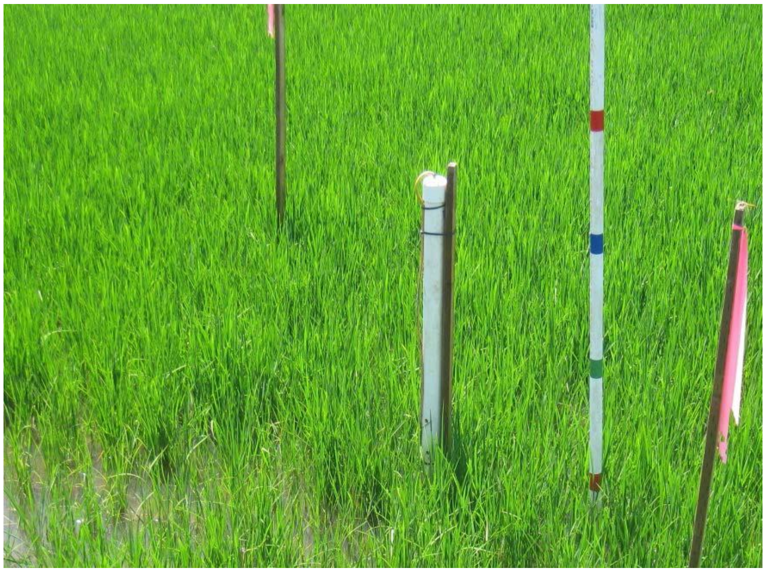
Figure A2. **REBS, Inc. Q7.2 Net Radiometer**

Figure A3. **Kipp & Zonen NR Lite Net Radiometer**

Figure A4. **REBS, Inc. HFT3 Heat Flux Plate**

Figure A5. **PVC Pipe with Float and Hinge**

Figure A6. A Global Water Instrumentation, Inc. WL400 Water-Level



Note: The water-level recorder (yellow cable) was inserted into a PVC stand pipe (2011–2012) with the sensor tip at the soil surface. Holes in the PVC allowed water to enter the standpipe and maintain the water level inside equal to that outside.

Figure A7. Water-Level Recorder Mounted in PVC Horizontally in 2013

Figure A8. **RM Young 81000RE 3-D Sonic Anemometer**

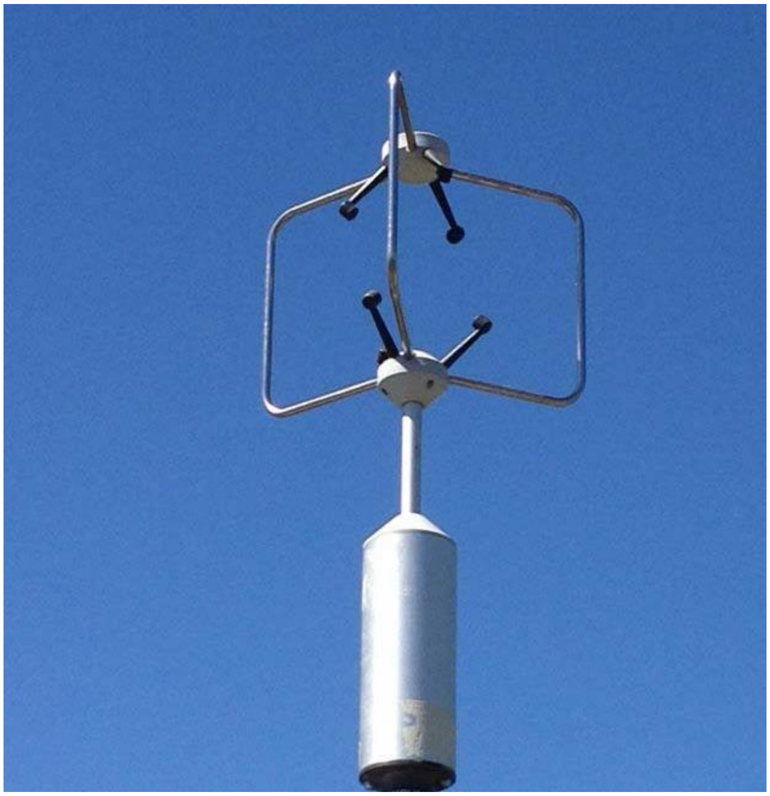
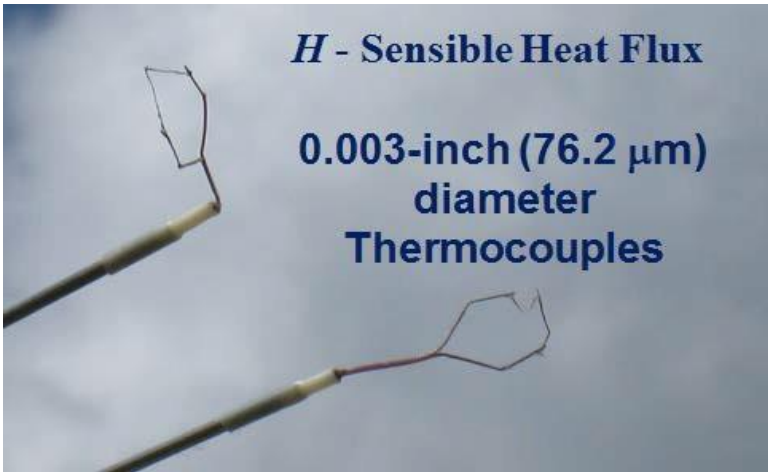


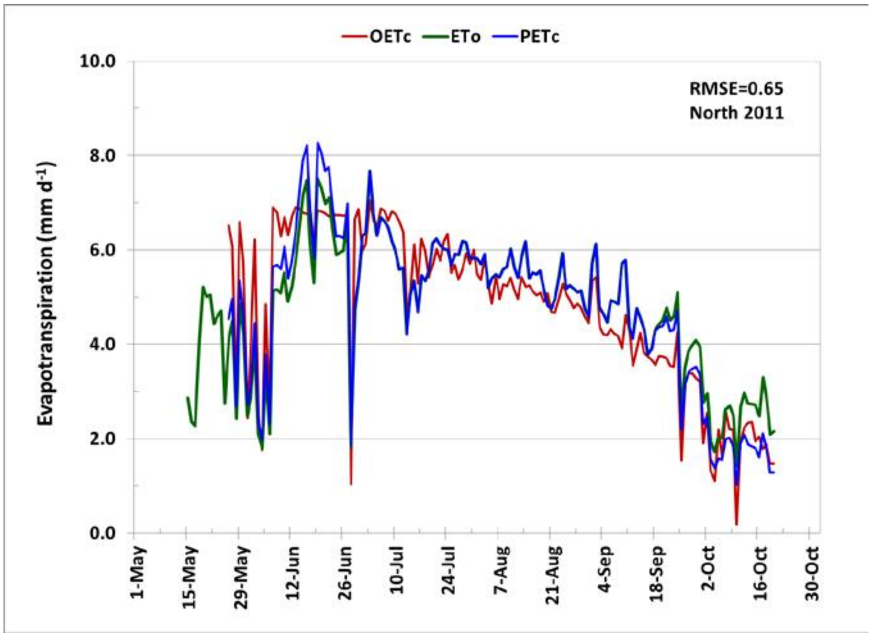
Figure A9. **Fine-wire Chromel-Constantan Thermocouple for Measuring High-Frequency Temperature for Surface Renewal Estimates of Sensible Heat Flux**



Appendix B. Plots of Reference Evapotranspiration, Observed Crop Evapotranspiration, and Predicted Crop Evapotranspiration Curves (2011–2013)

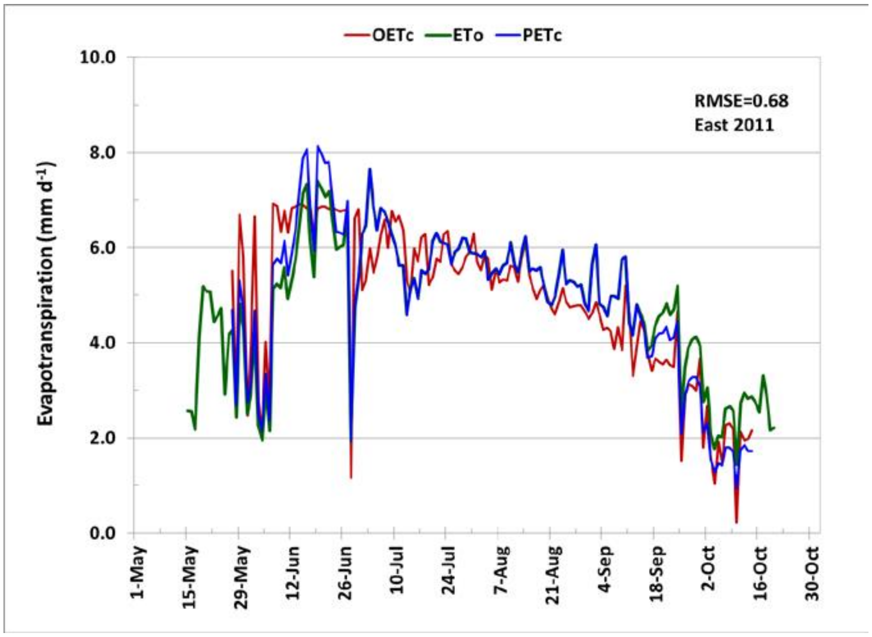
The plots in Appendix B show the daily standardized reference evapotranspiration (ETo) from Spatial California Irrigation Management Information System (CIMIS), the predicted crop evapotranspiration (ETc) which was estimated using the typical rice crop coefficient (Kc) curve that was adjusted for the observed length of season, and the observed ETc from field measurements during the 2011 through 2013 seasons. The Spatial CIMIS ETo data were selected from the CIMIS website using the latitude and longitude of the studied rice field.

Figure B1. **Daily Evapotranspiration for ETo, Kc PETc, and OETc from the North Rice Field (2011)**



Note:
ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error
During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B2. **Daily Evapotranspiration for ETo, Kc PETc, and OETc from the East Rice Field (2011)**

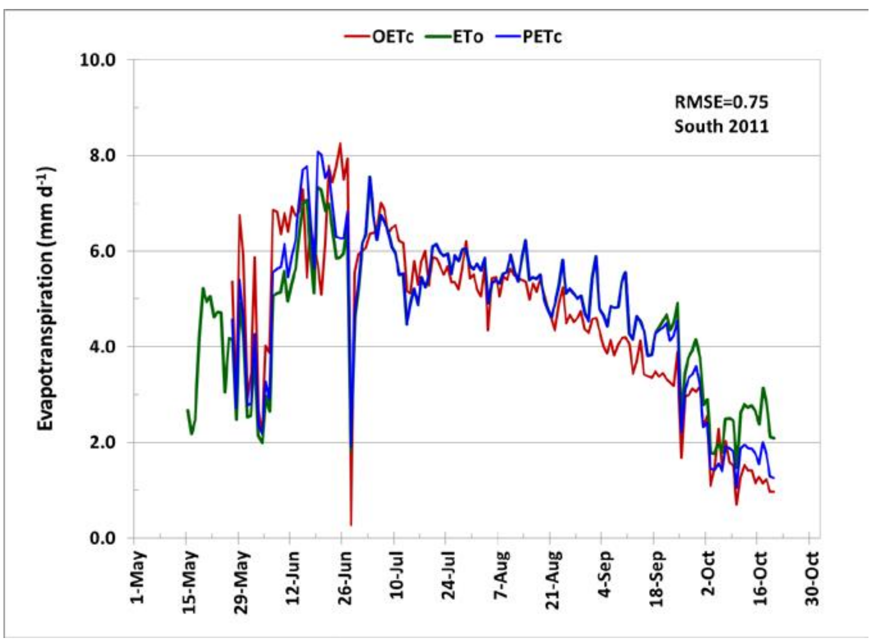


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B3. **Daily Evapotranspiration for ETo, Kc PETc, and OETc from the South Rice Field (2011)**

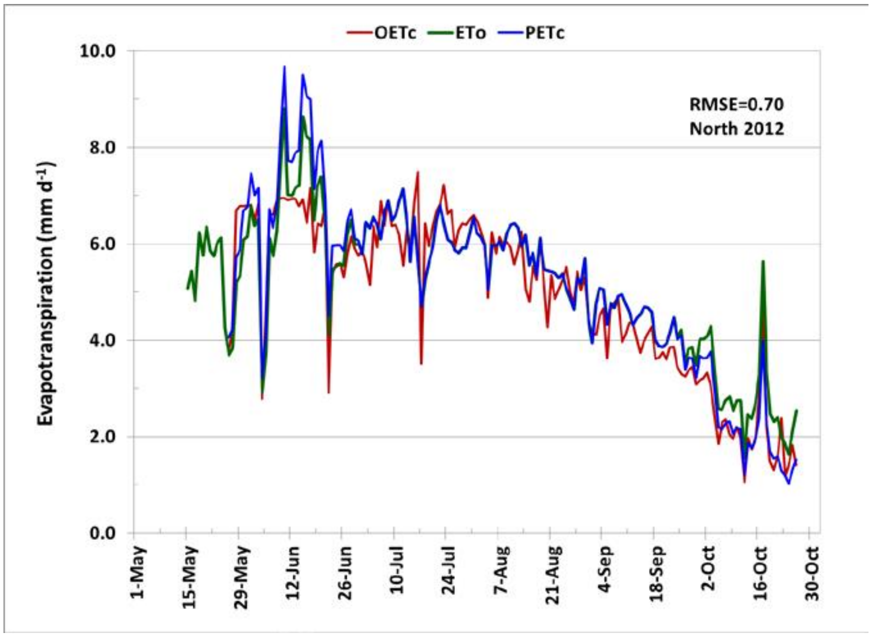


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B4. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the North Rice Field (2012)

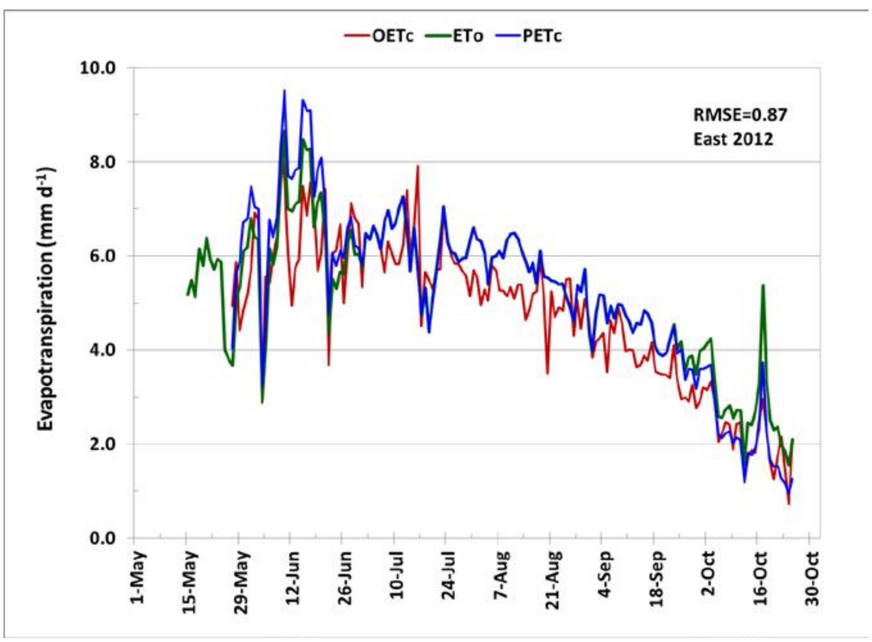


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B5. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the East Rice Field (2012)

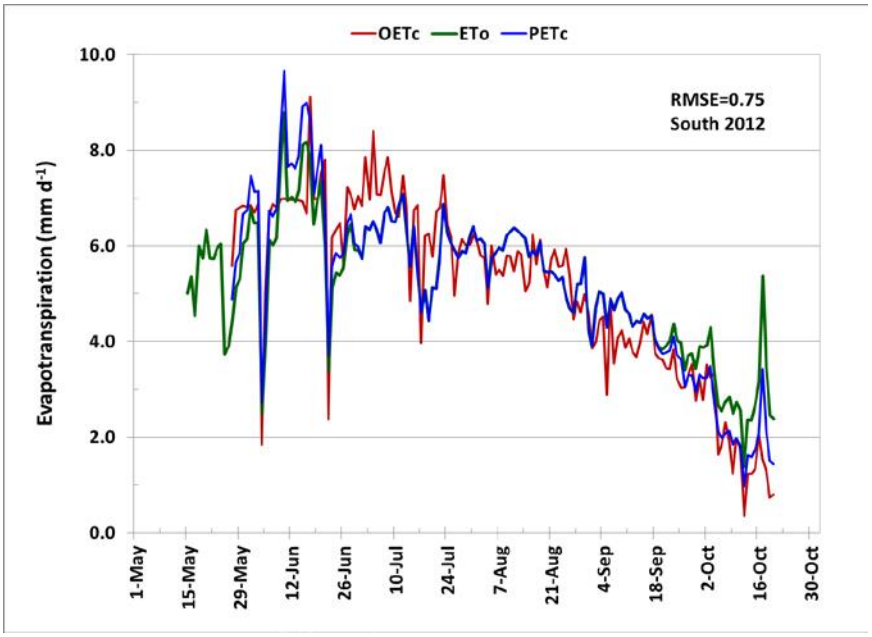


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B6. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the South Rice Field (2012)

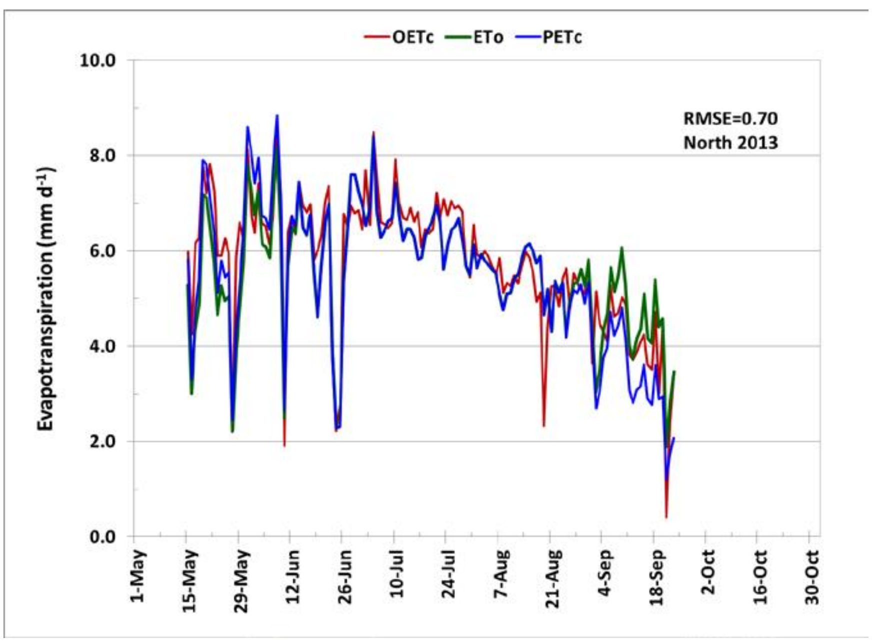


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B7. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the North Rice Field (2013)

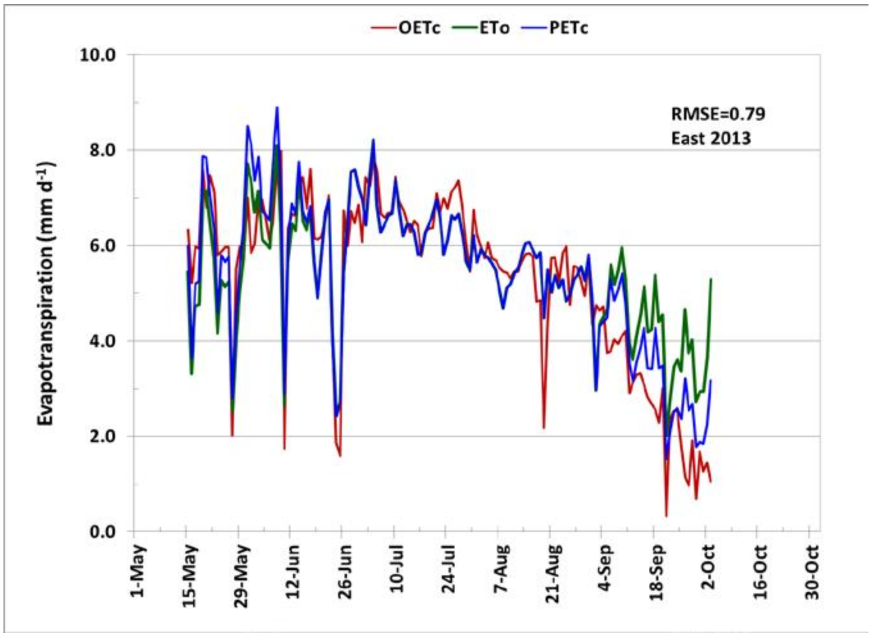


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B8. **Daily Evapotranspiration for ETo, Kc PETc, and OETc from the East Rice Field (2013)**

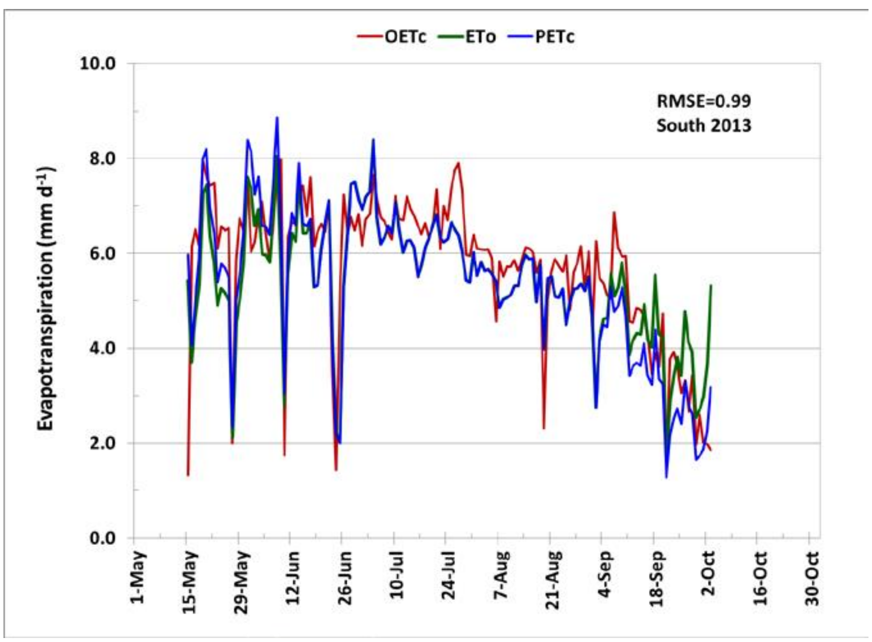


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure B9. **Daily Evapotranspiration for ETo, Kc PETc, and OETc from the South Rice Field (2013)**



Note:

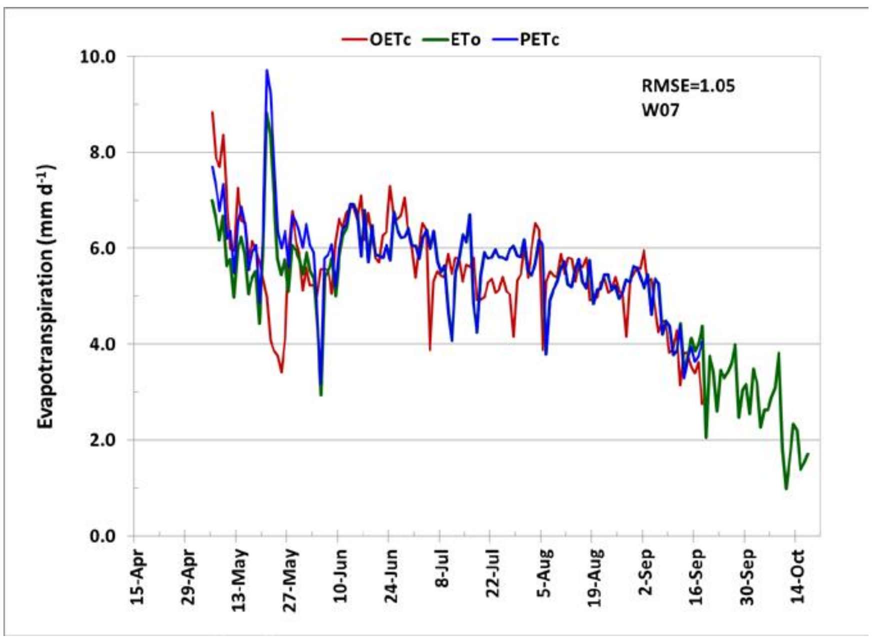
ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Appendix C. Plots of Reference Evapotranspiration, Observed Evapotranspiration, and Predicted Evapotranspiration Curves (2007–2009)

The plots in Appendix C show the daily standardized reference evapotranspiration (ETo) from Spatial California Irrigation Management Information System (CIMIS), the predicted crop evapotranspiration (ETc), which was estimated using the typical rice crop coefficient (Kc) curve that was adjusted for the observed length of season, and the observed ETc from field measurements during the 2007 through 2009 seasons. The Spatial CIMIS ETo data were selected from the CIMIS website using the latitude and longitude of the studied rice field. The stations were in adjacent fields in each year, so the ETo values are identical for both the drill-seeded and wet-seeded fields in each year.

Figure C1. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the Wet-Seeded Rice Field (2007)

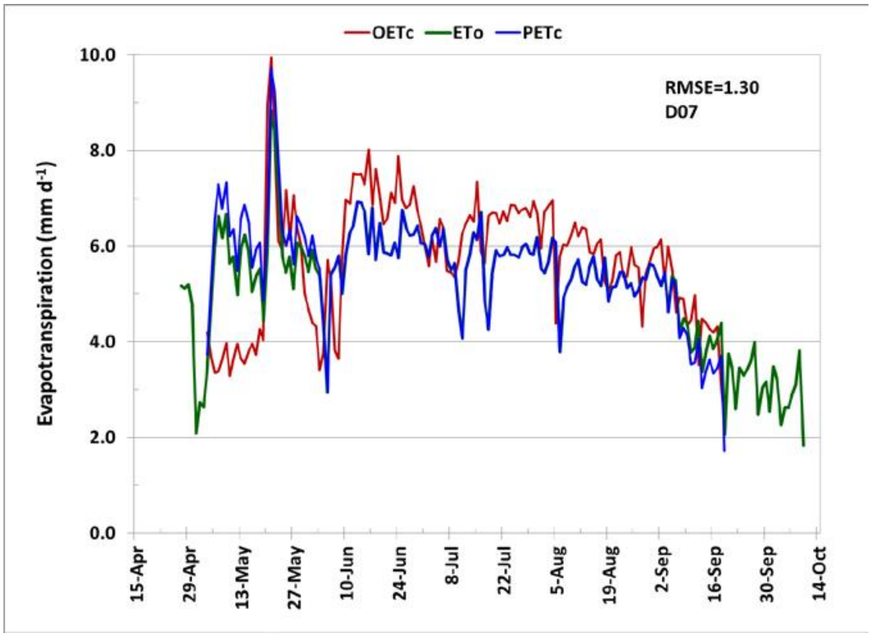


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure C2. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the Drill-Seeded Rice Field (2007)

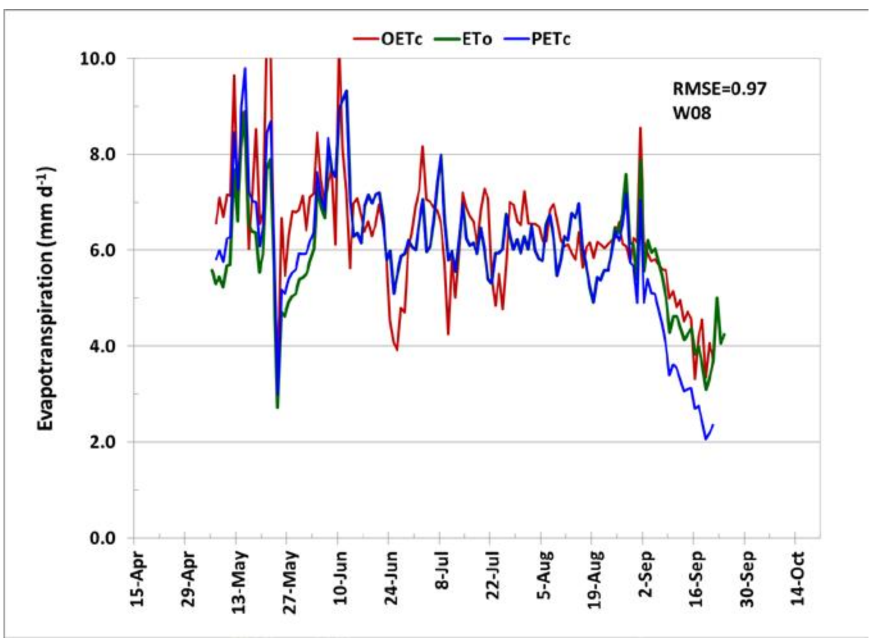


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure C3. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the Wet-Seeded Rice Field (2008)

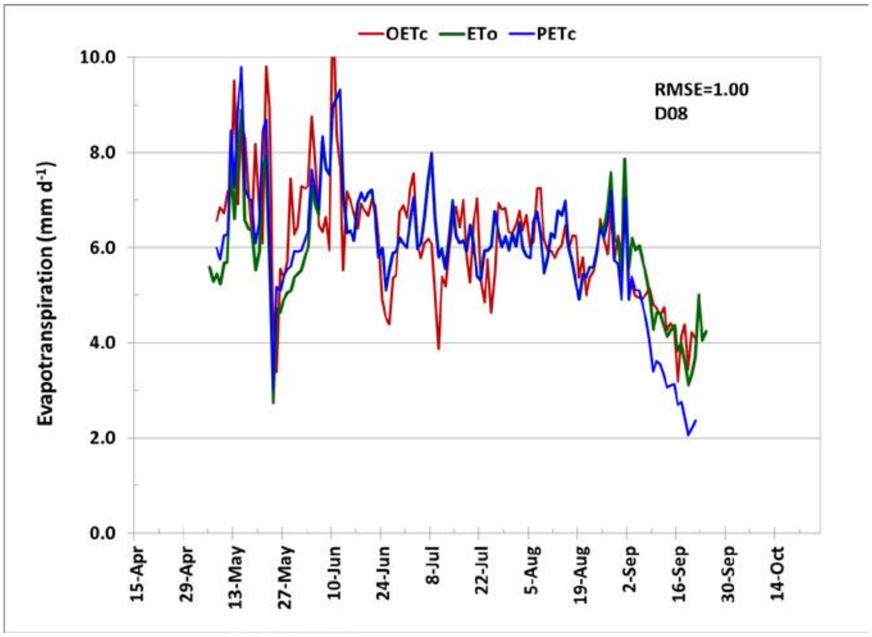


Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

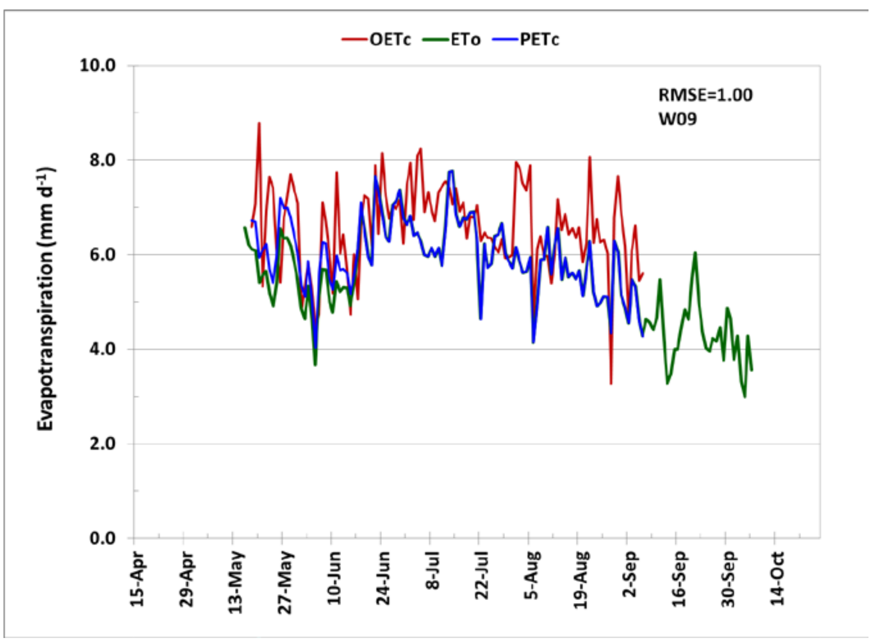
During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure C4. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the Drill-Seeded Rice Field (2008)



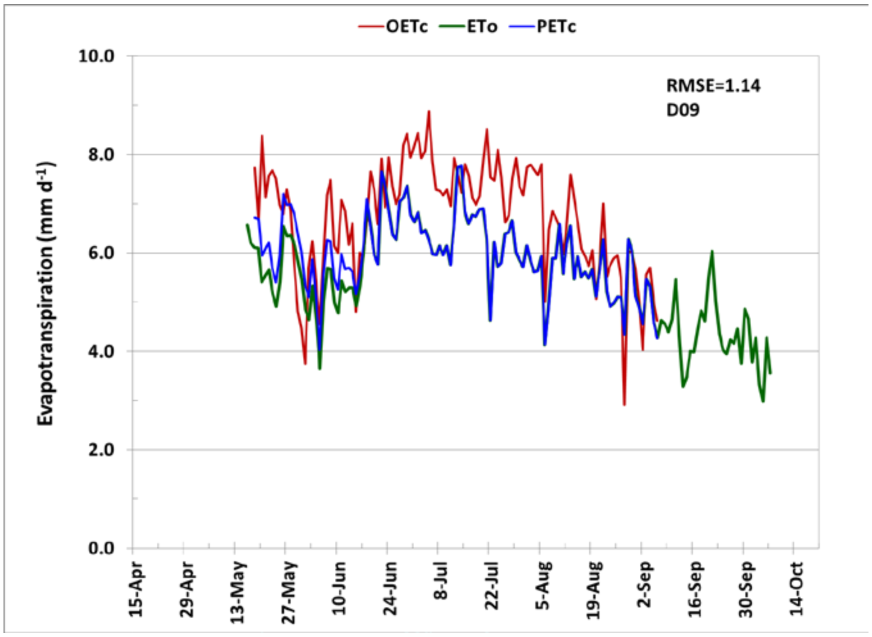
Note:
ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error
During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure C5. Daily Evapotranspiration for ETo, Kc PETc, and OETc from the Wet-Seeded Rice Field (2009)



Note:
ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error
During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Figure C6. **Daily Evapotranspiration for ETo, Kc PETc, and OETc from the Drill-Seeded Rice Field (2009)**



Note:

ETo = reference evapotranspiration, Kc = crop coefficient, OETc = observed crop evapotranspiration, PETc = predicted crop evapotranspiration, RMSE = root mean square error

During midseason, the green ETo line is behind the blue PETc line because the Kc = 1.00.

Appendix D. Information from Seed and Drying Purveyors

This appendix includes information provided by seed and drying purveyors for rice seed distribution, and for rice-crop drying. The data were used in conjunction with field observations by University of California, and DWR field staff, to help establish the growing-season planting and harvest dates for rice. Average dates for rice seed distribution for planting, and rice crop reported for drying, were determined using 50 percent of the total weight for each respective activity.

The following is a communication requesting information from the Butte County Rice Growers Association regarding average dates for distribution of half the rice seed, by weight, for planting.

Hi Carl,

It was a pleasure talking with you again on the phone this week.

As I've mentioned in our previous conversations, I work for the California Department of Water Resources, in the Division of Statewide Integrated Water Management. The reason that we are seeking the information regarding drying information for harvested rice is that we are in the process of refining the crop coefficient (K_c) for rice that has not been revisited since 1986, in DWR Bulletin 113-4, *Crop Water Use in California*. The study results will be used to inform the California Water Plan and provide a better understanding of rice water use in the Sacramento Valley during the growing season. The drying information for harvested rice will provide us with an additional source of information regarding the average harvest date (approximately 50 percent of the fields harvested by weight) for the rice growing season.

As additional background for the study, we have recently been working with the general managers of Western Canal, Butte, Richvale, and Sutter Extension water and irrigation districts. It was they who suggested that using the dates for seed distribution for planting could potentially help with our work. We have also been working closely with U.C. Farm advisors Bruce Linquist and Cass Mutters who have been helping by providing technical assistance and input. The study's principal investigator is Dr. Richard Snyder, U.C. Davis, Professor Emeritus.

We greatly appreciate any information you are able to provide, so please feel free to contact me if you should have any questions or need additional information.

Thank you for your offer of assistance and your time.

Sincerely yours,

Tom

Tom Filler
Division of Statewide Integrated Water Management
Department of Water Resources
(916) 653-5272
Thomas.Filler@water.ca.gov
http://www.water.ca.gov/planning/
www.waterplan.water.ca.gov

Hi Tom,

Here is the results from the last 13 years (2004 – 2016)

Year	Soak Date	Plant Date	Date
2016	5/10/16	5/12/16	12.00
2015	5/5/15	5/7/15	7.00
2014	5/12/14	5/14/14	14.00
2013	5/5/13	5/7/13	7.00
2012	5/19/12	5/21/12	21.00
2011	5/13/11	5/15/11	15.00
2010	5/19/10	5/21/10	21.00
2009	5/7/09	5/9/09	9.00
2008	5/4/08	5/6/08	6.00
2007	5/10/07	5/12/07	12.00
2006	5/22/06	5/24/06	24.00
2005	5/17/05	5/19/05	19.00
2004	5/3/04	5/5/04	5.00
			172.00
		Number of years	13.00
		Average planting date	13.23

The average plant date is May 13th. We take the soak date and add two days to it (usually when it is planted). It was interesting to note that the later planted dates corresponded with some of our poorer yielding years. No substitute for planting early.
Hope this helps with your study.

Thanks,
Carl

Carl Hoff
President and CEO
Butte County Rice Growers Assn.

The following is a communication requesting information from the DePue Warehouse Company regarding average dates for distribution of half the rice seed, by weight, for planting.

Hi Kevin,

It was a pleasure to talk with you on the phone today.

As I mentioned, I work for the California Department of Water Resources, in the Division of Statewide Integrated Water Management. The reason that we are seeking information regarding seed distribution for planting, is that we are in the process of refining the crop coefficient (K_c) for rice that has not been revisited since 1986, in DWR Bulletin 113-4, *Crop Water Use in California*. The study results will be used to inform the California Water Plan and provide a better understanding of rice water use in the Sacramento Valley during the growing season. The rice seed distribution dates for planting will provide us with an additional source of information regarding the average planting date (approximately 50 percent of the fields planted) for the growing season.

As additional background regarding the study, we have recently been working with the general managers of Western Canal, Butte, Richvale, and Sutter Extension water and irrigation districts. It was they who suggested that the dates for seed distribution for planting could potentially help with our work. We have also been working closely with U.C. Farm advisors Bruce Linquist and Cass Mutters who have been helping by providing technical assistance and input. The study's principal investigator is Dr. Richard Snyder, U.C. Davis, Professor Emeritus.

If you should have any questions, or need additional information, please do not hesitate to contact me. We greatly appreciate any information you are able to provide and thank you for your offer of assistance and your time.

Sincerely yours,
Tom

Tom Filler
Division of Statewide Integrated Water Management
Department of Water Resources
(916) 653-5272
tfiller@water.ca.gov
http://www.water.ca.gov/planning/
www.waterplan.water.ca.gov

Hello Tom,

I have attaced an excel sheet (shown as Table D1) of DePue's seed information that you talked to Kevin about.

Nan Dennis

Table D1. Rice Seed Process Dates, by Year

Rice Variety	Process Date for 50% (by weight) of Seed for Planting					
M-206	May 9, 2011	May 14, 2012	May 1, 2013	May 12, 2014	May 4, 2015	May 6, 2016
All	May 9, 2011	May 13, 2012	April 30, 2013	May 12, 2014	May 3, 2015	May 7, 2016

Source: De Pue Warehouse Co.

The following is a communication with the Butte County Rice Growers Association regarding information for average rice drying dates for half the crop, by weight, related to harvest.

From: Filler, Thomas@DWR [mailto:Thomas.Filler@water.ca.gov]
Sent: Thursday, June 22, 2017 11:08 AM
To: Carl Hoff
Subject: Rice Harvest Drying Information

Hi Carl,

It was a pleasure talking with you again on the phone this week.

As I've mentioned in our previous conversations, I work for the California Department of Water Resources, in the Division of Statewide Integrated Water Management. The reason that we are seeking the information regarding drying information for harvested rice is that we are in the process of refining the crop coefficient (K_c) for rice that has not been revisited since 1986, in DWR Bulletin 113-4, *Crop Water Use in California*. The study results will be used to inform the California Water Plan and provide a better understanding of rice water use in the Sacramento Valley during the growing season. The drying information for harvested rice will provide us with an additional source of information regarding the average harvest date (approximately 50 percent of the fields harvested by weight) for the rice growing season.

As additional background for the study, we have recently been working with the general managers of Western Canal, Butte, Richvale, and Sutter Extension water and irrigation districts. It was they who suggested that using the dates for seed distribution for planting could potentially help with our work. We have also been working closely with U.C. Farm advisors Bruce Linquist and Cass Mutters who have been helping by providing technical assistance and input. The study's principal investigator is Dr. Richard Snyder, U.C. Davis, Professor Emeritus.

We greatly appreciate any information you are able to provide, so please feel free to contact me if you should have any questions or need additional information.

Thank you for your offer of assistance and your time.

Sincerely yours,

Tom

Tom Filler
Division of Statewide Integrated Water Management
Department of Water Resources
(916) 653-5272
Thomas.Filler@water.ca.gov
http://www.water.ca.gov/planning/
www.waterplan.water.ca.gov

Hi Tom,
I received clearance from my board to send the information. I reviewed the last 13 years (2004 to 2016). I calculated the midpoint of harvest based upon 50% of the total deliveries for each year. I averaged the total of those dates and it works out to be October 5th.
Let me know if you need anything else.

Regards,
Carl

The following is a communication with the DePue Warehouse Company regarding information for average rice drying dates for half the crop, by weight, related to harvest.

From: Filler, Thomas@DWR [mailto:Thomas.Filler@water.ca.gov]
Sent: Thursday, June 22, 2017 11:35 AM
To: Kevin Dennis <kevin@depuewhse.com>
Subject: Rice Harvest Drying Information

Hi Kevin,

It was a pleasure talking with you again on the phone this week.

As I've mentioned in our past conversations, I work for the California Department of Water Resources, in the Division of Statewide Integrated Water Management. As we discussed, we are seeking information regarding approximately 50 percent of the rice fields harvested by weight rice for the past several years. The reason that we are seeking this information, is that we are in the process of refining the crop coefficient (K_c) for rice that has not been revisited since 1986, in DWR Bulletin 113-4, *Crop Water Use in California*. The study results will be used to inform the California Water Plan and provide a better understanding of rice water use in the Sacramento Valley during the growing season. The drying information for harvested rice will provide us with an additional source of information regarding the average harvest date (approximately 50 percent of the rice fields harvested by weight) for the rice growing season.

As additional background regarding the study, we have recently been working with the general managers of Glenn Colusa, RD 108, Western Canal, Butte, Richvale, and Sutter Extension water and irrigation districts. We have also been working closely with U.C. Farm advisors Bruce Linquist and Cass Mutters who have been helping by providing technical assistance and input. The study's principal investigator is Dr. Richard Snyder, U.C. Davis, Professor Emeritus.

If you should have any questions, or need additional information, please do not hesitate to contact me.

We greatly appreciate any information you are able to provide and thank you for your offer of assistance and your time.

Sincerely yours,
Tom

Tom Filler

Division of Statewide Integrated Water Management
Department of Water Resources
(916) 653-5272
Thomas.Filler@water.ca.gov
http://www.water.ca.gov/planning/
www.waterplan.water.ca.gov

Hi Tom,

Here is the information you requested for DePue Warehouse Co:
2015
Oct 1st: 923,528.61

2014
Oct 9th: 1,031,123.00

2013
Sept 24th: 725,751.09

Best,

Victor Kuechler | Information Technology
De Pue Warehouse Co.
O: 530-473-5361 | C: 530-330-0448

Appendix E. Monthly Summaries of Flow Data for Water Deliveries

This appendix includes water delivery information obtained by DWR staff from the U.S. Department of the Interior's Bureau of Reclamation Central Valley Operations Office. Data were supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only), and the U.S. Geological Survey. Surface water data for California were taken from the National Water Information System. Data presented in this appendix are only those years used for the CalSIMETaw model in Phase II of the of the study.

Table E1. **Reclamation District 1004 Flow Summary (acre-feet)**

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Apr–Sep
1987	6,346	-	-	-	-	-	3,707	11,059	11,851	10,300	7,979	1,969	46,865
1988	6,642	-	-	-	-	-	4,262	12,105	11,990	15,658	12,802	3,936	60,753
1989	7,989	-	-	-	-	-	3,160	9,294	10,400	13,163	12,320	3,719	52,056
1990	231	-	-	-	-	-	4,191	11,483	11,228	13,743	10,935	3,757	55,337
1991	7,905	-	-	-	-	-	1,223	5,800	5,603	5,772	4,776	1,535	24,709
1992	0	-	-	-	-	-	130	6,493	5,881	6,761	6,982	1,470	27,717
1993	5,906	-	-	-	-	-	1,761	10,719	9,262	11,597	10,415	3,048	46,802
1994	4,938	-	-	-	-	-	4,779	9,590	9,294	10,398	7,695	695	42,451
1995	868	-	-	-	-	-	929	8,418	8,484	8,797	8,491	3,356	38,475
1996	5,800	-	-	-	-	-	794	10,114	10,276	10,878	7,792	1,716	41,570
1997	8,401	-	-	-	-	-	3,484	10,254	9,161	10,335	7,599	1,164	41,997
1998	12,569	-	-	-	-	-	0	8,067	7,821	13,249	10,851	1,925	41,913
1999	5,791	-	-	-	-	-	1,540	10,444	9,188	13,341	8,787	3,316	46,616
2000	13,586	-	-	-	-	-	2,707	10,150	8,549	11,926	10,983	1,271	45,586
2001	10,700	-	-	-	-	-	2,428	13,384	15,193	12,582	10,314	4,435	58,336
2002	8,785	-	-	-	-	-	5,423	11,036	13,785	14,911	8,464	3,434	57,053
2003	13,425	-	-	-	-	-	862	8,955	9,252	14,555	10,594	3,311	47,529
2004	11,768	-	-	-	-	-	3,679	10,657	13,298	11,526	7,744	2,187	49,091
2005	11,527	-	-	-	-	-	1,414	4,415	7,456	10,467	9,958	3,714	37,424
2006	10,201	-	-	-	-	-	0	5,504	8,462	12,536	8,307	4,208	39,017
2007	8,332	-	-	-	-	-	1,494	12,104	11,204	10,251	6,775	2,728	44,556
2008	9,176	-	-	-	-	-	3,743	10,729	12,205	9,917	7,320	3,525	47,439
2009	11,301	-	-	-	-	-	3,543	7,474	8,158	14,599	5,461	2,169	41,404
2010	8,620	-	-	-	-	-	623	8,019	9,594	13,080	7,957	2,079	41,352
2011	7,068	-	-	-	-	-	310	8,846	7,436	9,721	8,047	2,636	36,996
2012	4,960	-	-	-	-	-	106	9,823	10,898	11,149	6,653	1,549	40,178
2013	8,412	-	-	-	-	-	5,135	8,807	8,442	10,408	8,056	1,246	42,094
2014	12,843	-	-	-	-	-	504	6,150	6,314	7,568	3,349	1,110	24,995
2015	10,622	-	-	-	-	-	2,220	5,656	8,255	8,057	2,716	1,313	28,217
2016	6,052	-	-	-	-	-	-	-	-	-	-	-	-
Average	8,025	-	-	-	-	-	2,212	9,157	9,619	11,284	8,280	2,501	43,053

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Apr–Sep
Maximum	13,586	-	-	-	-	-	5,423	13,384	15,193	15,658	12,802	4,435	60,753
Minimum	0	-	-	-	-	-	0	4,415	5,603	5,772	2,716	695	24,709

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

Note: Location is on the left bank of the Sacramento River at Mile 111.80.

Table E2. Western Canal Intake Flow Summary (acre-feet)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
1987	13,140	19,710	18,700	1,400	0	0	12,070	45,180	46,240	47,460	40,430	11,390	255,720	202,770
1988	14,770	17,320	3,110	322	0	0	5,130	50,430	43,710	57,520	43,230	8,460	244,002	208,480
1989	13,460	8,260	5,820	0	0	0	2,450	46,400	46,750	55,600	44,720	11,760	235,220	207,680
1990	5,860	10,940	6,030	1,080	0	0	13,830	48,110	43,380	55,550	42,090	8,920	235,790	211,880
1991	13,800	11,010	8,070	234	0	0	1,460	33,970	36,820	35,100	33,060	8,930	182,454	149,340
1992	11,520	16,110	9,480	0	0	0	1,530	49,910	36,230	35,900	30,560	4,630	195,870	158,760
1993	12,530	13,540	6,740	36	0	0	416	32,990	28,650	53,960	47,190	15,300	211,352	178,506
1994	15,480	16,280	9,070	720	0	0	14,010	47,330	42,150	43,810	29,220	3,080	221,150	179,600
1995	24,720	12,690	5,390	230	0	0	1,000	16,680	29,810	50,970	46,930	18,130	206,550	163,520
1996	20,285	23,310	9,876	1,361	0	0	2,269	36,180	46,239	58,623	46,019	9,467	253,628	198,797
1997	27,572	18,760	5,113	0	0	0	12,625	55,248	50,553	57,199	36,541	4,723	268,334	216,889
1998	15,150	21,963	7,583	2,190	0	0	260	35,125	28,742	55,267	47,437	12,246	225,963	179,078
1999	24,313	23,984	8,707	3,761	0	0	4,899	58,229	45,060	61,212	47,101	11,831	289,099	228,333
2000	33,088	32,148	24,785	6,992	0	0	6,900	52,308	51,297	60,545	43,170	10,122	321,356	224,342
2001	30,056	27,652	20,487	6,159	0	0	6,748	54,982	48,420	51,669	40,574	12,071	298,818	214,465
2002	43,388	20,400	7,882	292	0	0	16,062	52,980	55,555	61,319	37,133	5,978	300,990	229,027
2003	30,056	27,652	20,487	6,159	0	0	6,748	54,982	48,420	51,669	40,574	12,071	298,818	214,465
2004	27,989	33,445	14,819	4,116	0	0	19,622	57,572	59,300	60,083	39,882	8,567	325,394	245,026
2005	34,669	22,455	15,181	1,559	0	0	4,171	40,812	39,828	61,119	48,478	12,030	280,302	206,438
2006	26,763	30,077	14,269	2,162	0	0	0	40,681	50,450	59,980	51,344	15,318	291,044	217,773
2007	24,496	35,915	15,527	5,746	0	0	10,354	62,178	57,487	63,816	47,821	9,271	332,610	250,927
2008	26,454	43,920	17,336	3,888	0	0	15,818	55,103	57,172	56,616	43,398	9,782	329,486	237,890
2009	31,700	28,153	19,972	10,078	0	0	11,748	50,886	53,466	64,687	44,021	9,900	324,611	234,708
2010	29,506	40,719	17,076	7,853	0	0	0	39,705	43,771	61,396	51,907	17,663	309,596	214,443
2011	15,497	35,835	14,069	5,720	0	0	2,781	44,013	40,598	60,920	53,137	12,944	285,515	214,393
2012	17,361	39,729	23,734	9,673	0	0	375	45,860	49,611	59,659	48,978	11,518	306,498	216,001
2013	22,167	41,506	10,526	8,690	0	0	14,065	60,454	51,777	62,846	40,546	7,864	320,441	237,552
2014	38,676	41,501	25,663	11,897	0	2	4,187	51,795	48,419	53,005	32,141	8,704	315,990	198,251
2015	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2016	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average	23,017	25,535	13,054	3,654	0	0	6,840	47,146	45,711	55,625	42,773	10,452	273,807	208,548

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
Maximum	43,388	43,920	25,663	11,897	0	2	19,622	62,178	59,300	64,687	53,137	18,130	332,610	250,927
Minimum	5,860	8,260	3,110	0	0	0	0	16,680	28,650	35,100	29,220	3,080	182,454	149,340

Sources: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

U.S. Geological Survey. Surface water data for California taken from the National Water Information System.

Note: Intake located at Thermalito Afterbay near Oroville, California.

Table E3. **Richvale Canal Intake Flow Summary (acre-feet)**

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
1987	2,240	3,920	3,920	672	0	0	4,830	15,480	16,400	17,810	16,480	3,810	85,562	74,810
1988	3,080	4,930	2,530	292	0	0	3,920	12,950	15,860	17,850	12,680	2,970	77,062	66,230
1989	2,920	2,790	2,750	466	0	0	3,130	14,870	16,710	19,010	16,230	5,330	84,206	75,280
1990	4,005	3,120	1,880	179	0	0	5,820	14,040	17,350	20,200	15,900	4,010	86,504	77,320
1991	2,590	6,160	4,370	290	0	0	1,330	6,390	7,660	8,580	8,020	2,630	48,020	34,610
1992	65	6,830	5,500	411	0	0	1,340	10,140	8,980	11,120	11,700	2,010	58,096	45,290
1993	3,100	4,410	3,410	657	0	0	246	14,660	13,200	18,790	17,660	6,370	82,503	70,926
1994	7,940	6,190	3,730	355	0	0	11,540	27,850	34,410	40,070	31,540	7,950	171,575	153,360
1995	1,340	8,570	8,670	2,090	0	0	1,140	12,930	16,710	21,950	21,990	9,160	104,550	83,880
1996	6,149	13,898	10,917	5,183	0	0	2,177	18,115	19,150	23,175	20,265	3,255	122,284	86,138
1997	9,965	15,951	15,166	3,293	0	0	9,041	20,656	21,733	24,696	16,750	1,650	138,900	94,526
1998	12,032	13,476	12,436	3,903	0	0	143	14,975	15,634	23,855	24,008	7,696	128,158	86,311
1999	7,734	15,749	14,106	6,621	0	0	3,658	23,554	20,858	27,263	24,428	5,867	149,837	105,628
2000	9,540	19,503	17,191	11,397	0	0	2,424	20,499	22,326	26,904	22,274	4,270	156,329	98,698
2001	14,481	17,921	18,252	9,098	0	0	5,330	23,966	22,425	24,974	16,901	2,886	156,234	96,482
2002	15,439	16,405	15,291	8,047	0	0	8,598	19,226	23,246	26,037	16,873	5,994	155,157	99,975
2003	20,561	13,924	14,059	9,796	0	0	67	12,347	18,627	23,074	19,636	8,168	140,259	81,919
2004	10,502	18,668	13,773	9,578	0	0	10,024	24,379	25,605	27,124	18,365	3,765	161,784	109,261
2005	12,054	16,308	18,510	13,380	0	0	2,469	15,660	16,739	27,570	24,627	6,343	153,660	93,408
2006	8,932	19,626	14,204	6,002	0	0	0	18,250	21,784	27,314	24,833	8,073	149,018	100,255
2007	9,759	24,026	20,890	12,561	0	0	5,568	21,981	24,904	28,260	21,092	3,160	172,201	104,965
2008	10,677	21,418	14,735	2,346	0	0	9,709	21,084	23,474	21,777	16,229	2,563	144,012	94,836
2009	14,099	14,763	10,550	3,701	0	0	7,553	17,409	22,169	25,099	18,545	2,917	136,806	93,693
2010	13,698	20,483	15,564	6,442	0	0	0	15,642	18,659	23,905	19,396	5,647	139,436	83,248
2011	7,694	14,456	13,037	7,692	0	0	1,516	17,820	17,962	23,540	22,802	5,068	131,586	88,708
2012	7,216	19,379	19,337	8,537	0	0	65	16,909	19,533	24,008	21,122	5,069	141,174	86,706
2013	6,240	16,996	12,061	6,309	0	0	5,502	20,563	23,714	23,544	14,436	1,645	131,011	89,404
2014	10,161	20,654	18,478	7,866	0	3	2,835	16,475	18,440	17,371	11,389	3,203	126,876	69,713
2015	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2016	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average	8,365	13,590	11,618	5,256	0	0	3,928	17,458	19,438	23,031	18,792	4,696	126,171	87,342

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
Maximum	20,561	24,026	20,890	13,380	0	3	11,540	27,850	34,410	40,070	31,540	9,160	172,201	153,360
Minimum	65	2,790	1,880	179	0	0	0	6,390	7,660	8,580	8,020	1,645	48,020	34,610

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

U.S. Geological Survey. Surface water data for California taken from the National Water Information System.

Note: Intake located at Thermalito Afterbay near Oroville, California.

Table E4. **Pacific Gas & Electric Company Intake Flow Summary (acre-feet)**

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
1987	0	121	215	10	0	0	341	746	837	847	614	15	3,746	3,400
1988	9	267	23	20	0	0	61	787	798	853	438	18	3,274	2,955
1989	12	82	121	0	0	0	98	863	823	918	731	68	3,716	3,501
1990	0	0	283	8	0	8	374	554	834	962	556	46	3,625	3,326
1991	0	254	80	0	0	0	128	441	587	598	527	82	2,697	2,363
1992	0	209	68	0	0	0	0	713	549	652	499	47	2,737	2,460
1993	0	165	73	0	0	0	0	628	512	883	787	133	3,181	2,943
1994	0	254	201	32	0	0	591	403	756	897	468	0	3,602	3,115
1995	117	251	50	7	0	0	75	561	580	928	858	133	3,560	3,135
1996	0	392	71	25	0	0	81	641	742	936	667	0	3,554	3,067
1997	422	133	97	0	0	0	1,196	849	1,890	1,864	889	0	7,341	6,688
1998	142	345	14	15	0	0	0	571	500	964	904	103	3,558	3,041
1999	98	331	61	26	0	0	109	831	783	1,029	928	107	4,303	3,787
2000	0	324	352	61	0	0	99	697	784	918	733	49	4,018	3,281
2001	274	144	133	38	0	0	201	719	958	938	819	32	4,256	3,668
2002	439	331	147	5	0	0	232	609	894	1,037	765	12	4,472	3,550
2003	155	382	106	50	0	0	0	597	586	1,035	944	197	4,051	3,359
2004	4	250	203	50	0	0	460	703	964	900	737	28	4,300	3,793
2005	0	528	113	0	0	0	0	657	601	984	946	49	3,878	3,237
2006	0	550	284	5	0	0	0	748	739	831	663	96	3,915	3,077
2007	0	447	275	73	0	0	65	861	843	851	603	60	4,077	3,283
2008	0	385	342	107	0	0	208	522	623	597	450	36	3,272	2,437
2009	0	389	186	27	0	0	104	604	532	766	458	22	3,086	2,485
2010	45	424	220	93	0	0	0	617	565	900	863	335	4,063	3,280
2011	13	470	236	30	0	0	0	627	585	785	859	166	3,771	3,022
2012	0	537	265	142	0	0	0	436	370	570	538	66	2,925	1,981
2013	0	403	136	85	0	0	398	621	730	811	526	88	3,799	3,174
2014	136	385	400	180	0	0	0	517	499	602	485	30	3,236	2,134
2015	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2016	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average	67	313	170	39	0	0	172	647	731	888	688	72	3,786	3,198

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
Maximum	439	550	400	180	0	8	1,196	863	1,890	1,864	946	335	7,341	6,688
Minimum	0	0	14	0	0	0	0	403	370	570	438	0	2,697	1,981

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

U.S. Geological Survey. Surface water data for California taken from the National Water Information System.

Note: Intake located at Thermalito Afterbay near Oroville, California.

Table E5. **Sutter-Butte Canal Intake Flow Summary (acre-feet)**

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
1987	22,770	6	0	0	0	0	42,540	93,740	91,460	90,820	83,620	46,020	470,976	448,200
1988	26,160	12,390	9,420	391	0	26,300	44,310	84,400	81,860	95,640	83,210	44,590	508,671	434,010
1989	25,740	11,650	10,540	1,590	0	0	14,310	94,360	88,540	97,510	93,180	45,670	483,090	433,570
1990	19,090	14,070	13,750	1,770	0	1,100	54,570	84,440	81,240	99,690	86,180	38,810	494,710	444,930
1991	33,100	15,230	13,240	902	5,180	10	4,060	51,460	49,910	51,300	47,690	24,640	296,722	229,060
1992	10,740	12,940	10,310	791	0	0	5,170	63,020	49,150	57,810	54,330	26,700	290,961	256,180
1993	21,930	14,670	13,600	2,980	0	0	2,210	76,580	67,400	95,210	88,190	50,020	432,790	379,610
1994	23,150	21,610	20,960	7,960	0	799	47,470	81,480	83,010	88,340	78,280	34,220	487,279	412,800
1995	31,310	19,320	20,160	5,000	0	0	3,170	69,890	79,000	95,640	87,290	53,140	463,920	388,130
1996	24,278	31,335	25,321	13,311	0	0	2,220	75,187	88,582	97,884	90,188	44,414	492,720	398,475
1997	31,666	27,180	22,576	2,061	0	8,136	50,848	93,223	86,440	91,537	72,789	33,183	519,640	428,021
1998	36,821	31,131	25,271	9,435	0	0	1,194	53,931	70,810	93,521	89,534	50,922	462,569	359,911
1999	31,424	31,014	26,509	12,325	0	0	16,017	101,931	88,364	96,099	88,086	49,242	541,010	439,738
2000	34,695	35,351	30,298	21,178	0	0	21,977	91,200	88,304	95,821	86,340	45,525	550,689	429,168
2001	35,671	38,269	37,626	23,609	0	0	22,548	94,689	88,602	89,534	83,921	47,786	562,255	427,079
2002	42,928	45,739	33,017	17,818	0	0	35,867	89,464	96,774	101,415	87,055	44,700	594,776	455,274
2003	51,888	52,360	42,450	22,048	0	0	1,960	49,898	90,327	98,658	86,579	58,699	554,866	386,120
2004	35,740	52,459	47,064	25,960	0	0	42,391	97,250	94,750	100,522	86,297	39,033	621,465	460,243
2005	41,613	51,711	47,175	32,426	0	0	7,303	87,769	87,868	100,681	89,831	47,576	593,952	421,027
2006	36,538	57,390	51,677	21,757	0	0	0	81,057	93,124	100,562	95,326	54,700	592,130	424,768
2007	39,535	55,617	53,000	35,407	0	0	39,501	102,823	93,342	98,102	88,145	41,804	647,276	463,718
2008	33,790	64,683	54,194	9,330	0	0	50,959	95,861	88,701	89,970	72,571	36,157	596,218	434,220
2009	33,957	52,296	44,245	20,713	0	0	34,877	88,145	85,269	89,871	81,124	39,031	569,530	418,318
2010	31,444	64,124	56,555	30,494	56	62	61	70,727	79,041	89,415	82,493	46,471	550,941	368,207
2011	29,472	55,787	45,896	30,145	0	0	4,090	88,752	79,490	94,413	91,339	47,036	566,420	405,120
2012	30,077	63,564	52,649	26,396	75	25	333	78,071	85,468	94,235	85,706	47,383	563,982	391,196
2013	34,114	62,618	42,827	22,877	0	1,853	35,443	96,714	90,863	95,742	81,717	33,122	597,890	433,601
2014	40,003	67,712	49,761	20,703	0	0	7,648	81,779	73,051	82,116	67,347	36,073	526,193	348,014
2015	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2016	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average	31,773	37,937	32,146	14,978	190	1,367	21,180	82,780	82,884	91,859	82,441	43,095	522,630	404,240

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
Maximum	51,888	67,712	56,555	35,407	5,180	26,300	54,570	102,823	96,774	101,415	95,326	58,699	647,276	463,718
Minimum	10,740	6	0	0	0	0	0	49,898	49,150	51,300	47,690	24,640	290,961	229,060

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

U.S. Geological Survey. Surface water data for California taken from the National Water Information System.

Note: Intake located at Thermalito Afterbay near Oroville, California.

Table E6. **Sutter Mutual Water Company Tisdale Plant Flow Summary (acre-feet)**

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Apr–Sep
1987	0	-	-	-	-	-	21,049	35,939	36,953	30,394	32,790	9,351	166,476
1988	1,025	-	-	-	-	-	10,320	34,106	32,811	40,446	31,884	8,909	158,476
1989	0	-	-	-	-	-	9,905	38,736	38,243	33,939	32,494	11,234	164,551
1990	0	-	-	-	-	-	21,318	27,274	30,847	38,155	32,653	9,262	159,509
1991	767	-	-	-	-	-	7,967	31,096	30,932	30,378	29,457	12,587	142,417
1992	286	-	-	-	-	-	8,941	35,726	31,618	29,088	29,236	5,246	139,855
1993	2,068	-	-	-	-	-	6,653	32,671	32,051	39,143	32,549	8,961	152,028
1994	2,551	-	-	-	-	-	17,948	31,610	35,842	37,749	30,753	4,680	158,582
1995	0	-	-	-	-	-	2,153	24,916	30,669	44,562	36,495	10,969	149,764
1996	2,912	-	-	-	-	-	5,881	26,087	34,405	39,093	26,968	7,265	139,699
1997	3,179	-	-	-	-	-	19,566	38,326	39,931	39,095	29,283	4,758	170,959
1998	3,607	-	-	-	-	-	1,110	11,119	17,016	36,386	32,911	11,536	110,078
1999	1,913	-	-	-	-	-	8,682	38,830	40,533	44,664	33,713	7,528	173,950
2000	0	-	-	-	-	-	12,086	37,731	44,798	50,164	34,882	5,515	185,176
2001	4,817	-	-	-	-	-	10,449	30,978	31,279	32,269	24,125	4,569	133,669
2002	1,562	-	-	-	-	-	13,016	30,371	32,269	35,257	28,868	6,525	146,306
2003	1,290	-	-	-	-	-	2,680	22,878	30,716	36,733	34,967	9,734	137,708
2004	1,569	-	-	-	-	-	15,143	40,115	41,571	49,190	35,177	5,907	187,103
2005	1,602	-	-	-	-	-	5,785	28,226	31,401	39,509	37,090	9,384	151,395
2006	0	-	-	-	-	-	405	37,366	41,162	48,704	46,417	9,194	183,248
2007	71	-	-	-	-	-	15,483	38,135	41,429	48,654	37,385	5,734	186,820
2008	0	-	-	-	-	-	22,963	44,519	44,153	43,607	34,008	6,160	195,410
2009	4,300	-	-	-	-	-	19,822	39,639	40,565	49,403	33,328	6,205	188,962
2010	0	-	-	-	-	-	2,401	35,557	38,098	46,081	41,240	6,958	170,335
2011	0	-	-	-	-	-	5,411	31,274	31,370	44,568	39,969	6,411	159,003
2012	0	-	-	-	-	-	1,615	32,264	32,688	41,745	35,169	6,784	150,265
2013	577	-	-	-	-	-	14,171	37,808	40,981	44,828	28,583	2,118	168,489
2014	7,802	-	-	-	-	-	4,753	25,883	27,639	32,447	23,754	4,573	119,049
2015	7,678	-	-	-	-	-	8,825	26,296	26,352	29,523	18,670	1,836	111,502
2016	5,293	-	-	-	-	-	-	-	-	-	-	-	-

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Apr–Sep
Average	1,829	-	-	-	-	-	10,224	32,603	34,770	39,854	32,580	7,238	157,268
Maximum	7,802	-	-	-	-	-	22,963	44,519	44,798	50,164	46,417	12,587	195,410
Minimum	0	-	-	-	-	-	405	11,119	17,016	29,088	18,670	1,836	110,078

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation’s Willows Field Office, Water and Land Division (long-term contracts only).

Note: Intake located on the left bank of the Sacramento River at Mile 63.75.

Table E7. Glenn-Colusa Irrigation District Sacramento River Diversion Summary (acre-feet)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
1987	40,515	-	-	-	-	-	89,404	135,299	155,627	149,794	148,719	56,183		735,026
1988	41,184	-	-	0	2,800	40,400	81,921	123,426	135,537	152,593	127,464	51,515		672,456
1989	47,471	44,800	14,400	0	0	1,000	70,590	132,730	149,404	162,610	154,319	60,808	838,132	730,461
1990	32,092	23,200	0	0	0	18,400	81,750	104,808	131,771	144,191	137,665	61,289	735,166	661,474
1991	45,762	31,900	0	3,300	14,400	800	48,496	105,028	115,599	123,657	98,444	48,943	636,329	540,167
1992	35,719	38,700	12,800	0	0	1,400	37,084	107,831	91,549	92,931	74,073	40,296	532,383	443,764
1993	32,642	22,700	0	0	0	300	39,192	101,050	90,887	101,938	76,100	51,310	516,119	460,477
1994	28,052	29,400	8,400	0	0	22,707	73,022	95,898	110,846	103,372	68,189	36,349	576,235	487,676
1995	39,465	28,500	0	0	0	0	35,804	83,003	94,483	113,791	93,828	53,149	542,023	474,058
1996	32,412	31,500	8,100	0	0	2,900	35,124	112,006	115,917	120,462	92,072	43,164	593,657	518,745
1997	44,044	37,100	0	0	0	21,000	81,005	121,141	114,939	114,706	84,418	38,373	656,726	554,582
1998	50,954	37,100	0	0	0	7,700	19,468	105,338	83,053	131,450	97,412	57,461	589,936	494,182
1999	41,364	43,400	0	0	600	1,500	46,562	137,126	121,100	136,030	80,642	53,960	662,284	575,420
2000	53,754	58,400	0	0	0	5,100	65,250	122,765	139,482	137,821	95,548	43,567	721,687	604,433
2001	58,395	55,200	35,600	21,900	6,700	5,100	75,280	140,493	133,479	137,467	124,510	45,972	840,096	657,201
2002	78,384	62,500	19,000	6,110	0	2,970	103,436	121,302	154,963	153,764	114,095	29,529	846,053	677,089
2003	61,562	56,400	25,877	23,291	5,947	4,592	43,449	123,213	133,462	156,548	118,732	38,601	791,674	614,005
2004	57,630	78,414	35,028	21,245	0	5,566	91,992	140,825	157,831	157,870	118,841	29,356	894,598	696,715
2005	88,116	61,973	48,155	26,666	0	2,428	39,328	119,662	132,542	159,894	136,410	54,599	869,773	642,435
2006	68,835	71,424	50,326	28,672	4,531	370	2,428	127,553	142,935	160,895	139,428	65,911	863,308	639,150
2007	57,404	40,616	1,561	40,616	1,561	11,070	87,466	148,266	152,740	147,698	123,088	44,372	856,458	703,630
2008	66,168	50,486	32,519	15,772	0	11,803	80,925	152,120	149,962	149,018	131,833	45,724	886,330	709,582
2009	76,727	19,189	15,669	13,057	0	6,199	69,526	142,394	141,524	153,744	116,391	35,585	790,005	659,164
2010	66,861	45,924	32,920	13,848	0	3,491	18,407	134,920	137,935	168,448	145,630	56,040	824,424	661,380
2011	45,780	68,097	43,213	7,556	5,124	6,671	36,499	132,922	129,299	161,650	146,845	52,384	836,040	659,599
2012	40,596	70,659	53,203	13,602	4,158	9,509	13,369	151,565	153,750	163,529	148,341	51,569	873,850	682,123
2013	53,323	70,823	28,127	7,136	4,734	20,901	79,002	148,252	162,842	168,424	124,059	36,511	904,134	719,090
2014	74,338	8,301	4,285	8,273	11,003	13,717	15,734	126,363	133,847	130,838	97,655	36,573	660,927	541,010
2015	35,869	9,847	1,988	2,591	3,742	16,658	35,152	108,605	113,170	117,746	87,707	32,976	566,051	495,356
2016	27,189	31,819	4,623	-	-	-	-	-	-	-	-	-	-	-
Average	50,754	43,870	16,993	9,058	2,332	8,723	55,057	124,342	130,361	140,444	113,878	46,623	737,200	610,705

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	Apr–Sep
Maximum	88,116	78,414	53,203	40,616	14,400	40,400	103,436	152,120	162,842	168,448	154,319	65,911	904,134	735,026
Minimum	27,189	8,301	0	0	0	0	2,428	83,003	83,053	92,931	68,189	29,356	516,119	443,764

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

Note: Intake is on the right bank of the Sacramento River at Mile 154.8.

Table E8. **Princeton-Cordua-Glenn Irrigation District Sacramento River Diversion Summary (acre-feet)**

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct–Sep	Apr–Sep
1987	0	-	-	-	-	-	4,701	8,423	9,034	9,622	9,708	2,475	43,963	43,963
1988	0	-	-	-	-	-	4,799	7,310	7,868	8,893	7,944	2,954	39,768	39,768
1989	0	-	-	-	-	-	3,903	7,782	8,300	9,040	8,661	3,310	40,996	40,996
1990	37	-	-	-	-	-	5,202	5,938	6,888	7,706	7,606	2,320	35,697	35,660
1991	373	-	-	-	-	-	3,750	7,367	8,148	7,373	6,711	3,190	36,912	36,539
1992	0	-	-	-	-	-	3,598	8,814	8,066	7,989	7,746	1,512	37,725	37,725
1993	813	-	-	-	-	-	1,819	8,848	8,926	11,317	10,605	3,392	45,720	44,907
1994	419	-	-	-	-	-	5,612	8,130	9,688	6,625	7,648	1,744	39,866	39,447
1995	885	-	-	-	-	-	576	3,120	7,475	7,840	7,443	3,084	30,423	29,538
1996	752	-	-	-	-	-	2,287	7,666	8,087	11,728	8,884	2,245	41,649	40,897
1997	1,541	-	-	-	-	-	4,966	8,971	8,739	10,469	7,930	855	43,471	41,930
1998	0	-	-	-	-	-	126	7,216	5,744	7,660	7,481	2,751	30,978	30,978
1999	0	-	-	-	-	-	3,202	9,936	8,421	9,997	9,882	5,075	46,513	46,513
2000	3,763	-	-	-	-	-	3,957	11,455	12,679	14,028	9,296	1,510	56,688	52,925
2001	5,173	-	-	-	-	-	6,004	11,364	10,771	11,758	9,638	2,095	56,803	51,630
2002	5,818	-	-	-	-	-	7,678	10,605	12,648	13,747	7,869	2,831	61,196	55,378
2003	5,084	-	-	-	-	-	2,992	11,804	11,486	13,726	8,656	1,259	55,007	49,923
2004	5,865	-	-	-	-	-	7,065	13,286	12,531	13,333	987	0	53,067	47,202
2005	2,979	-	-	-	-	-	5,037	12,428	12,127	15,662	11,435	2,882	62,550	59,571
2006	1,049	-	-	-	-	-	88	12,640	12,337	14,061	11,194	3,691	55,060	54,011
2007	1,130	-	-	-	-	-	8,322	13,869	14,186	14,660	9,709	2,077	63,953	62,823
2008	2,852	-	-	-	-	-	8,215	13,769	14,322	14,131	11,542	2,140	66,971	64,119
2009	5,150	-	-	-	-	-	7,910	13,066	13,073	13,649	9,435	1,502	63,785	58,635
2010	6,012	-	-	-	-	-	2,960	13,210	12,818	14,016	11,205	2,037	62,258	56,246
2011	3,051	-	-	-	-	-	2,281	12,675	9,926	12,768	9,265	2,455	52,421	49,370
2012	2,176	-	-	-	-	-	1,551	14,422	11,659	13,066	9,780	1,468	54,122	51,946
2013	4,307	-	-	-	-	-	8,136	11,644	11,720	10,864	8,723	1,229	56,623	52,316
2014	5,805	-	-	-	-	-	352	10,507	7,807	9,939	8,645	1,503	44,558	38,753
2015	2,425	-	-	-	-	-	2,326	10,112	8,797	9,860	8,556	955	43,031	40,606
2016	3,100	-	-	-	-	-	-	-	-	-	-	-	-	-
Average	2,352	-	-	-	-	-	4,118	10,220	10,147	11,225	8,765	2,226	49,027	46,701

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct–Sep	Apr–Sep
Maximum	6,012	-	-	-	-	-	8,322	14,422	14,322	15,662	11,542	5,075	66,971	64,119
Minimum	0	-	-	-	-	-	88	3,120	5,744	6,625	987	0	30,423	29,538

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

Note: Location is on the right bank of the Sacramento River at Mile 123.9.

Table E9. **Reclamation District 108 (Wilkins Slough) Sacramento River Diversion Summary (acre-feet)**

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Apr–Sep
1987	0	-	-	-	-	-	11,318	19,082	17,129	21,095	17,462	3,033	89,119
1988	299	-	-	-	-	-	4,350	14,616	18,445	22,690	16,456	2,764	79,321
1989	0	-	-	-	-	-	7,729	16,752	14,699	15,369	14,798	336	69,683
1990	0	-	-	-	-	-	11,135	17,320	17,879	23,448	16,005	475	86,262
1991	0	-	-	-	-	-	4,104	17,430	19,455	22,907	16,715	24	80,635
1992	0	-	-	-	-	-	6,336	22,690	21,509	25,364	16,254	1,861	94,014
1993	2,012	-	-	-	-	-	3,031	16,860	16,065	22,033	16,503	2,569	77,061
1994	26	-	-	-	-	-	11,761	15,045	21,784	21,616	10,372	0	80,578
1995	1,247	-	-	-	-	-	2,915	13,628	8,622	24,852	27,919	5,562	83,498
1996	1,973	-	-	-	-	-	1,951	15,274	14,515	23,409	21,879	4,612	81,640
1997	1,913	-	-	-	-	-	7,662	12,808	11,459	22,834	14,422	751	69,936
1998	0	-	-	-	-	-	802	11,774	11,623	20,474	20,106	1,864	66,643
1999	0	-	-	-	-	-	3,828	19,373	16,864	23,989	20,578	4,416	89,048
2000	3,554	-	-	-	-	-	4,482	21,785	23,478	23,129	14,019	901	87,794
2001	6,006	-	-	-	-	-	4,725	22,734	19,826	19,710	16,603	2,124	85,722
2002	5,802	-	-	-	-	-	10,101	21,983	23,008	21,014	11,309	1,576	88,991
2003	8,755	-	-	-	-	-	1,357	18,136	20,933	22,009	13,815	1,193	77,443
2004	3,505	-	-	-	-	-	7,140	24,559	22,857	21,087	12,269	713	88,625
2005	6,560	-	-	-	-	-	3,304	21,728	23,460	20,481	13,746	171	82,890
2006	3,673	-	-	-	-	-	0	22,285	27,076	23,536	18,649	6,375	97,921
2007	974	-	-	-	-	-	5,816	25,727	18,431	17,900	10,480	1,169	79,523
2008	1,014	-	-	-	-	-	7,724	32,196	29,828	20,995	11,782	951	103,476
2009	10,138	-	-	-	-	-	7,227	28,353	26,039	22,573	14,368	514	99,074
2010	1,481	-	-	-	-	-	726	21,253	24,654	22,154	17,216	3,189	89,192
2011	1,400	-	-	-	-	-	19,884	23,466	23,173	21,418	15,036	3,437	106,414
2012	13	-	-	-	-	-	723	26,982	28,039	23,794	19,298	4,351	103,187
2013	0	-	-	-	-	-	7,575	31,405	30,181	33,448	19,702	1,579	123,890
2014	6,492	-	-	-	-	-	566	20,448	19,817	23,250	14,957	2,911	81,949
2015	3,974	-	-	-	-	-	4,037	16,019	17,510	17,451	9,351	1,130	65,497
2016	0	-	-	-	-	-	-	-	-	-	-	-	-
Average	2,360	-	-	-	-	-	5,597	20,404	20,288	22,208	15,933	2,088	86,518

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Apr–Sep
Maximum	10,138	-	-	-	-	-	19,884	32,196	30,181	33,448	27,919	6,375	123,890
Minimum	0	-	-	-	-	-	0	11,774	8,622	15,369	9,351	0	65,497

Source: U.S. Department of Interior — Bureau of Reclamation Central Valley Operations Office. Data supplied by Reclamation's Willows Field Office, Water and Land Division (long-term contracts only).

Note: Location is on the right bank of the Sacramento River at Mile 63.2.

DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA